Multiwavelength Monitoring of the Supermassive Black Hole in the Galactic Center

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Research Issues

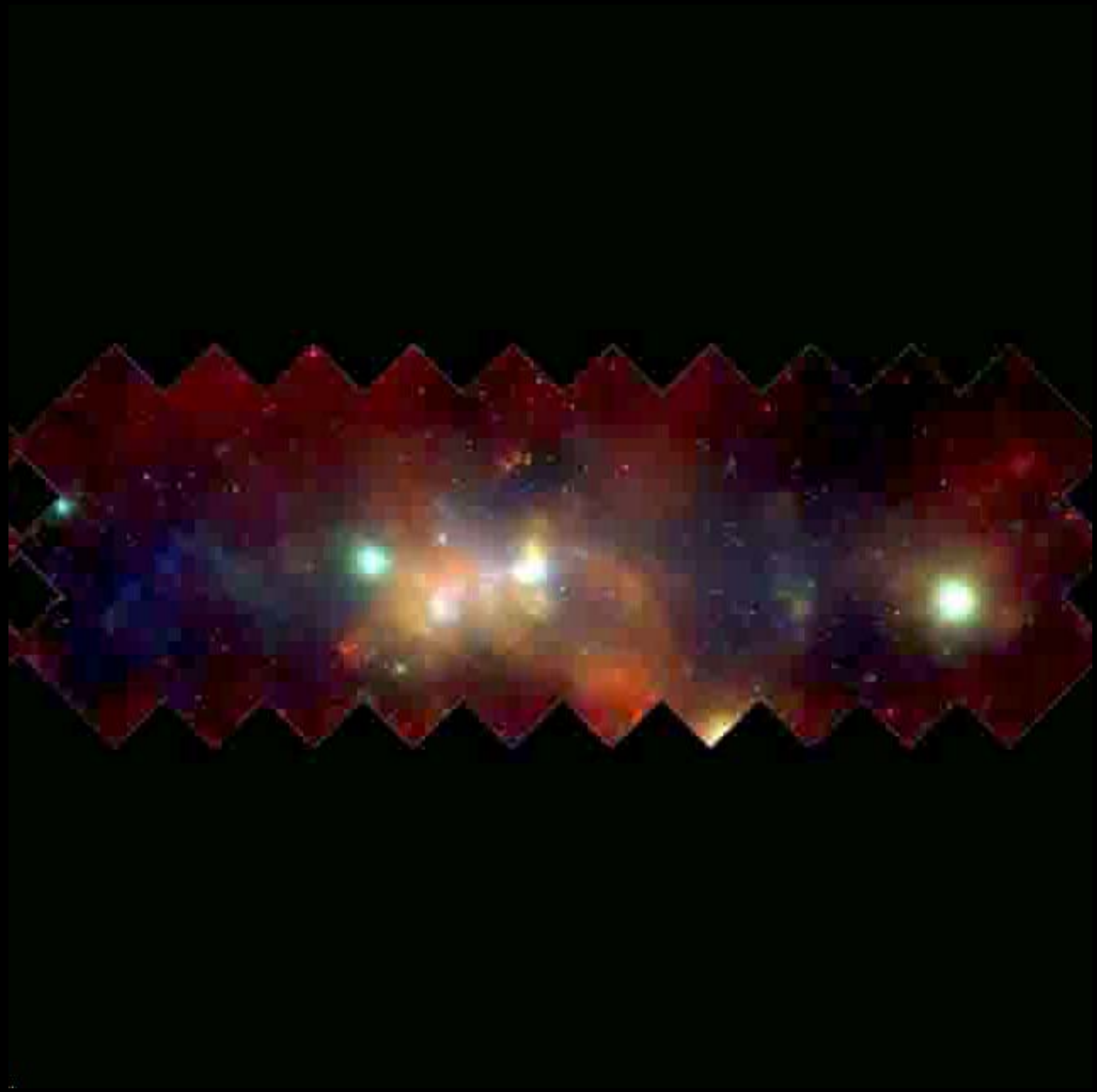
- Supermassive black hole at the Galactic Center: Sagittarius A*
  - Accretion physics
  - Emission mechanism of rapid X-ray/IR flares
  - Evidence for a bipolar outflow
  - Evidence for a possible X-ray jet
- High-mass star formation history in the Nuclear Bulge
- Supernova Remnants
- Colliding stellar winds and other interactions
- Origin of new X-ray structures in the field

X-ray View of the Galactic Center

Wang, Gotthelf, and Lang (2002)

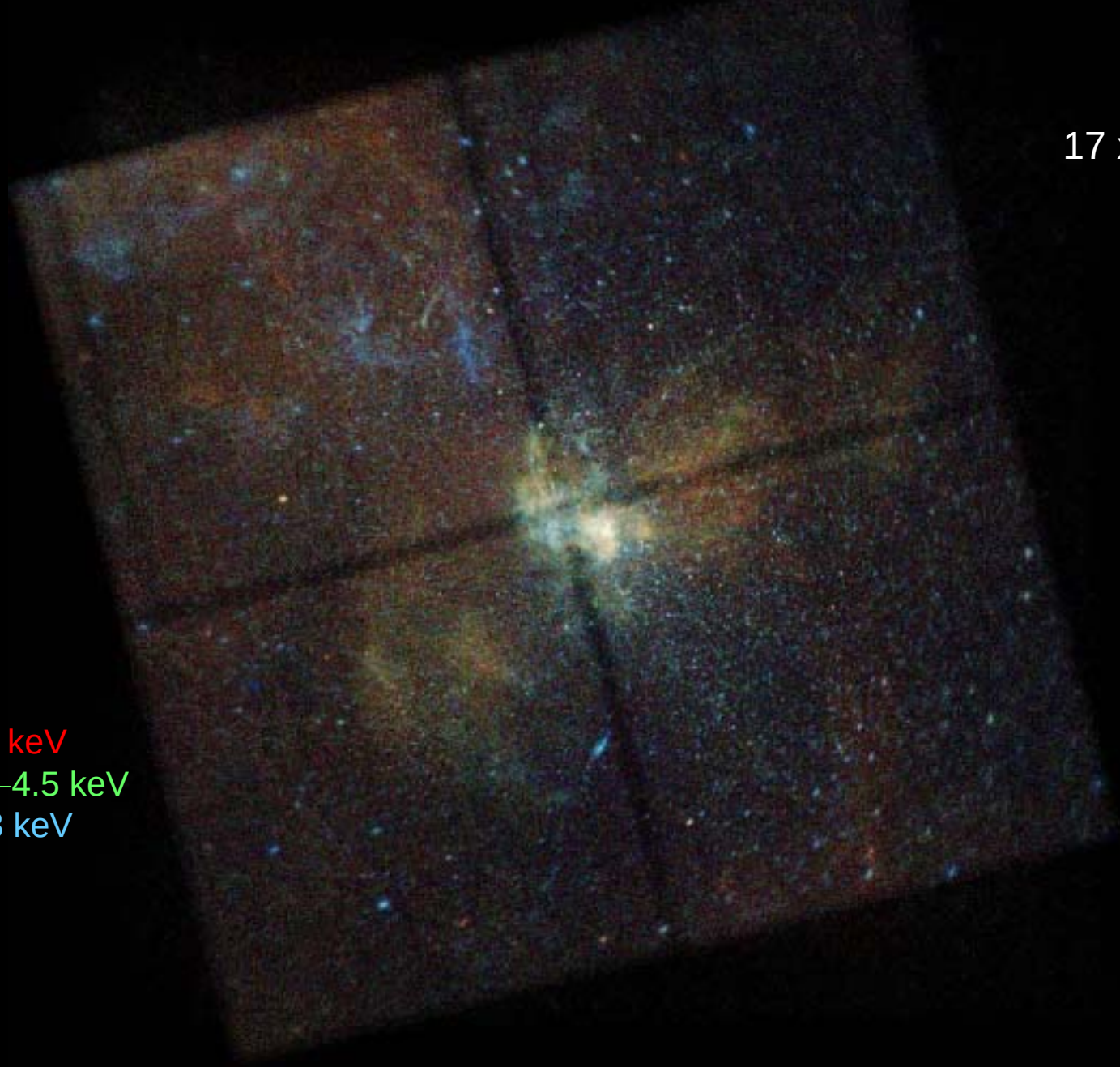
2 x 0.8 degrees

Zooming into the Galactic Center in X-rays



Animation Credit: NASA/CXC/SAO

Chandra Galactic Center Deep Field

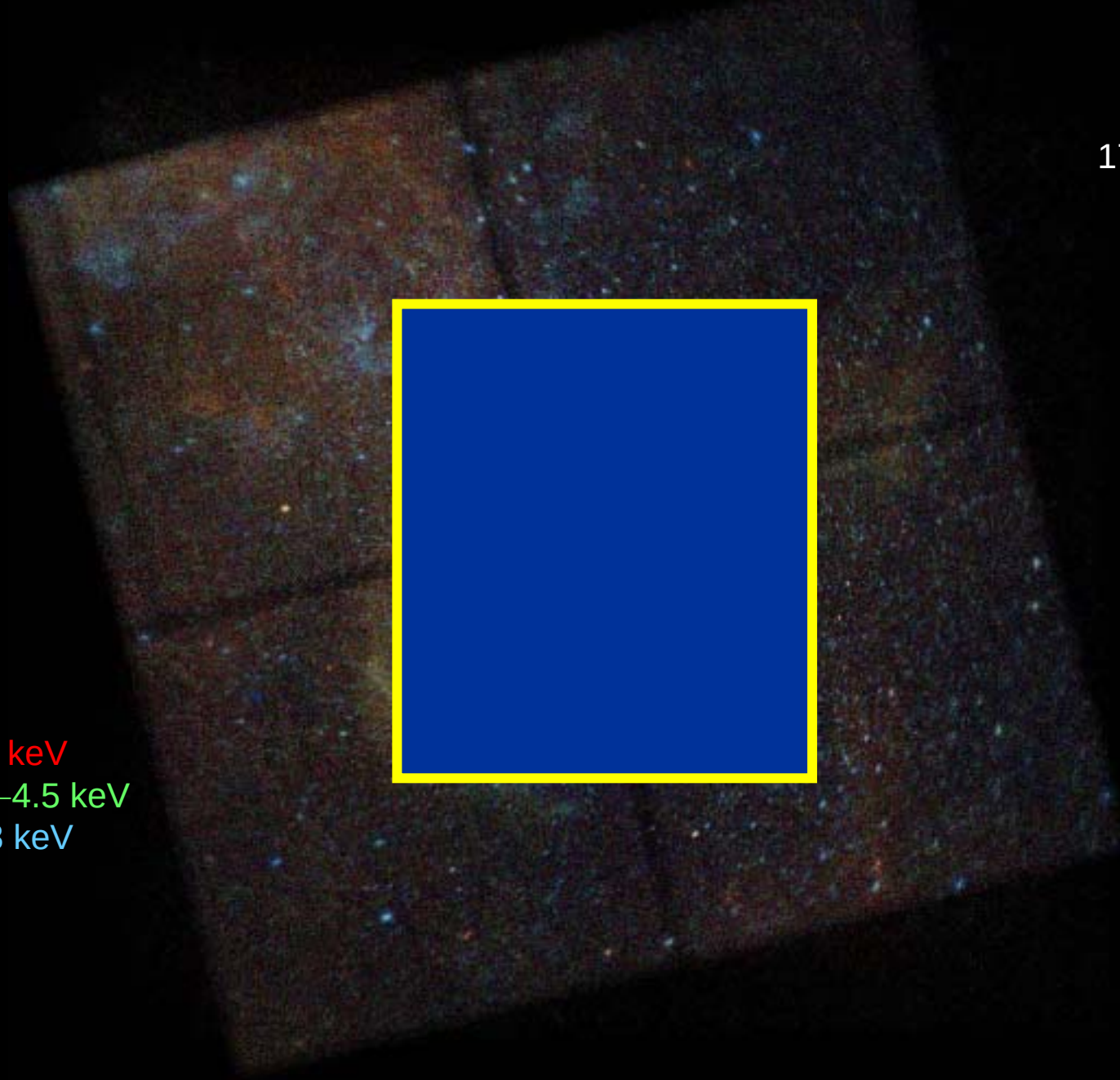


17 x 17 arcmin

590 ks

Red 2–3.7 keV
Green 3.7–4.5 keV
Blue 4.5–8 keV

Chandra Galactic Center Deep Field



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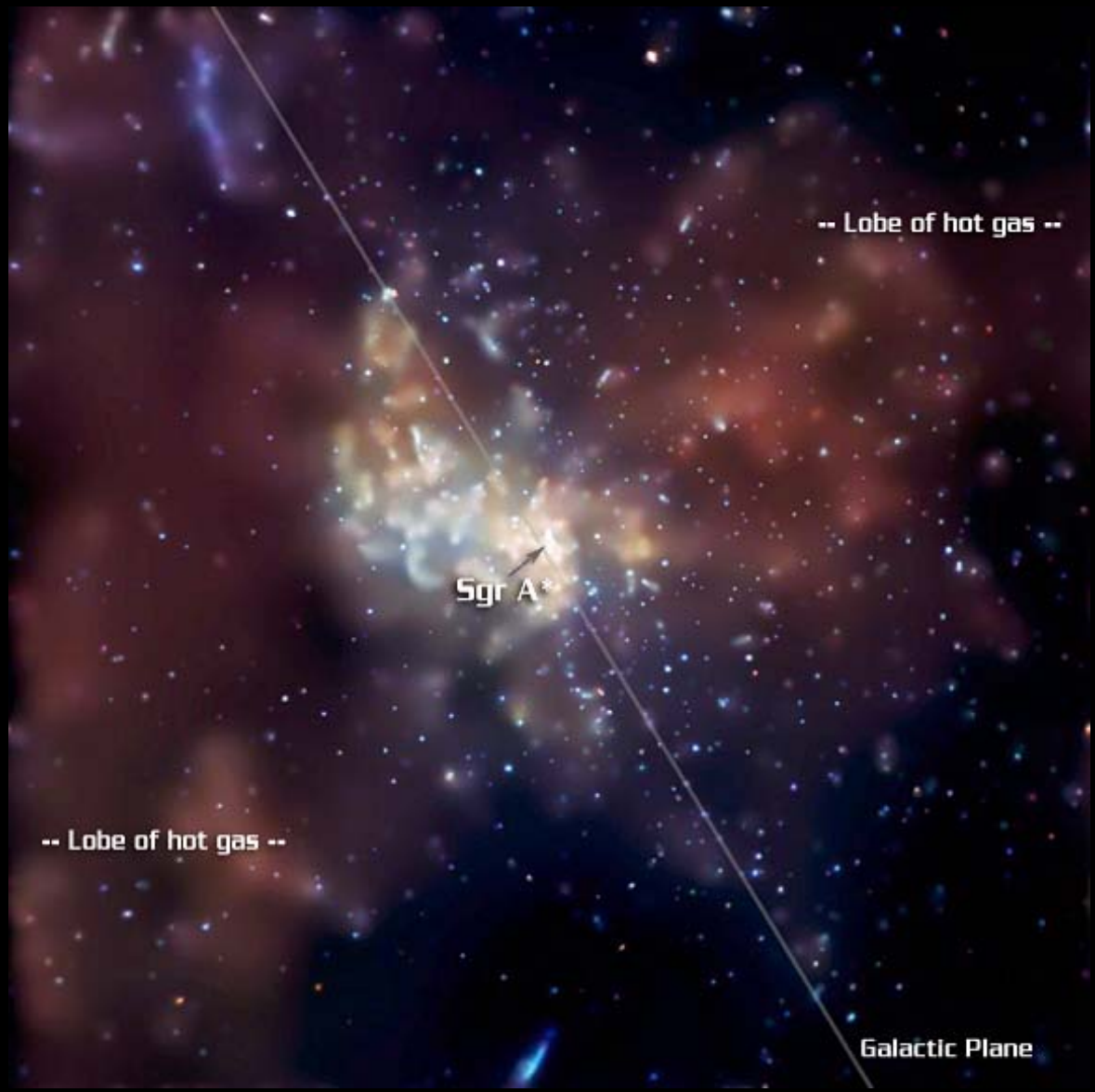
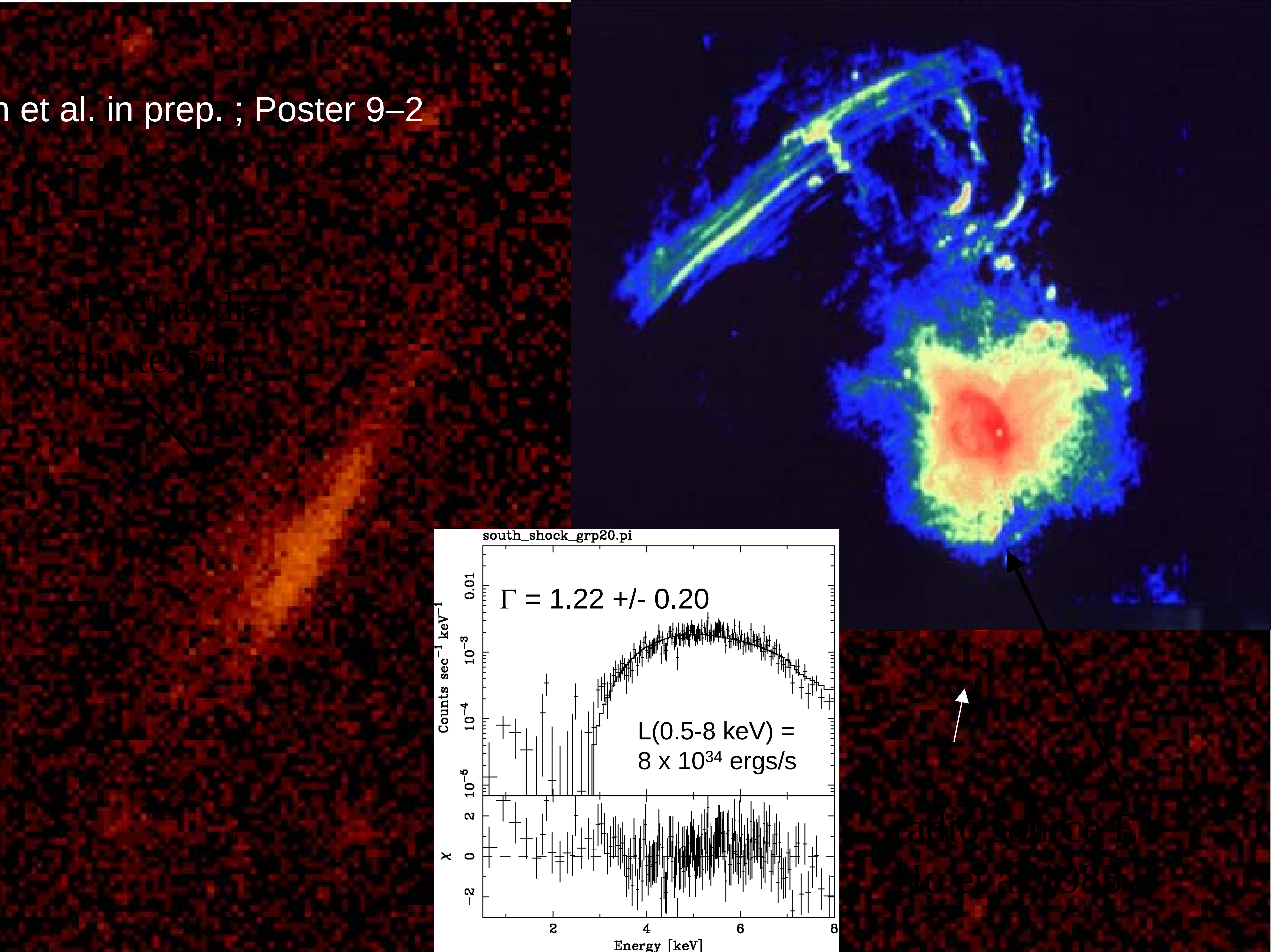
Chandra Galactic Center Deep Field



8.4 x 8.4 arcminutes

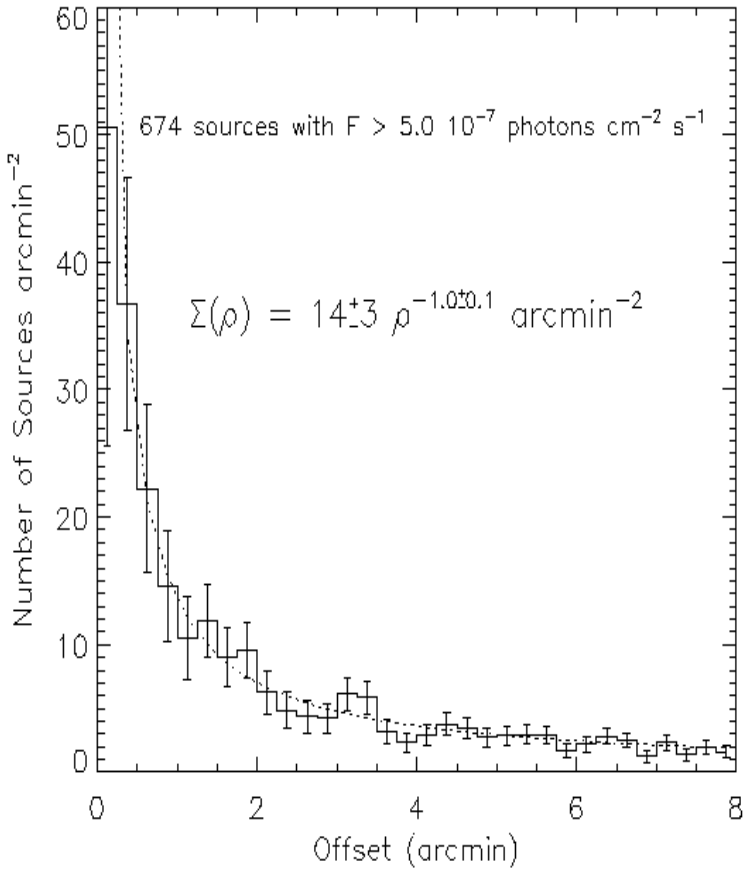

n et al. in prep. ; Poster 9–2
E1: Chandra counterpart
south_shock_grp20.pi
Γ = 1.22 +/- 0.20
L(0.5-8 keV) = 8 x 10^34 ergs/s
Counts sec^-1 keV^-1
χ
Energy [keV]
radio source E1
Ho et al. 1985

X-ray Point Sources

- 2287 sources have been resolved.
- 278 are of the foreground in the galactic center.
- About 40 are background AGN
- Sources have $L_X=10^{30}$-10^{33} erg s^{-1} (2-8 keV)

Muno et al. (2003)

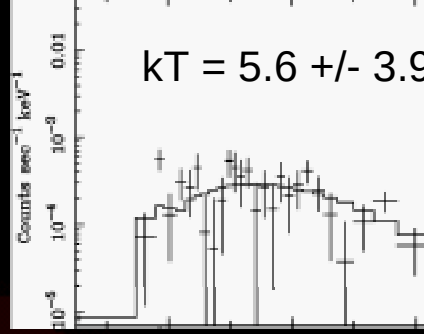
Spatial Distribution

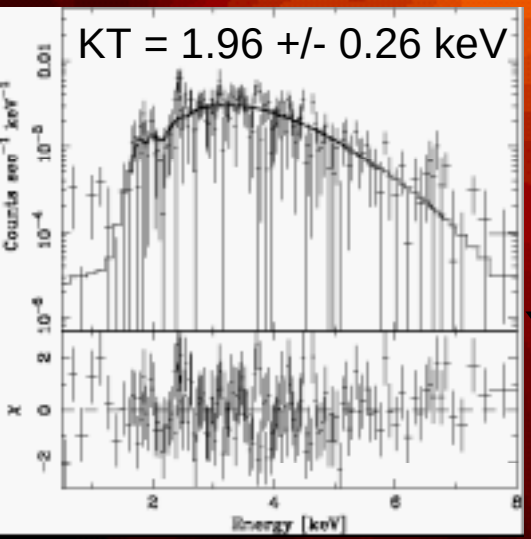


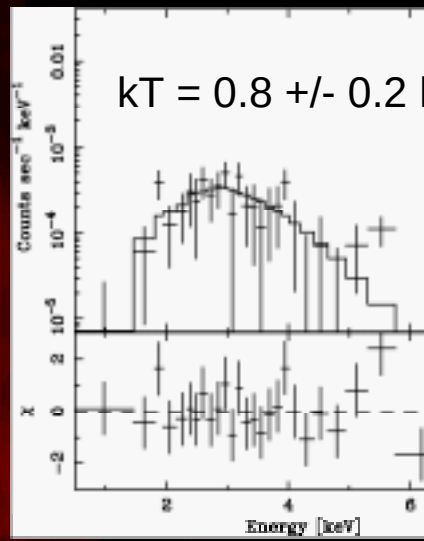
- Consistent with an isothermal sphere ($1/R^2$)
- Similar to spatial density of bright infrared stars in Nuclear Bulge
- Could provide important information about star formation history

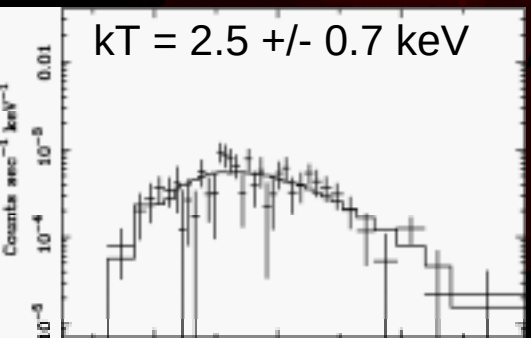
Bipolar Lobes

kT = 0.56 +/- 0.11 keV





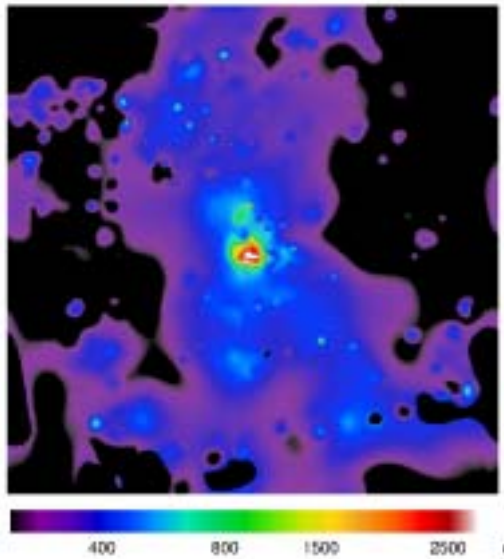


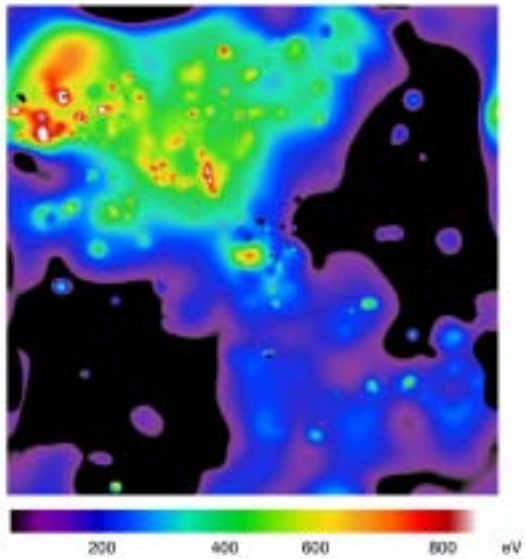


X-ray Emission-Line Equivalent-Width Maps

Fe Heα

(E ~ 6.7 keV)



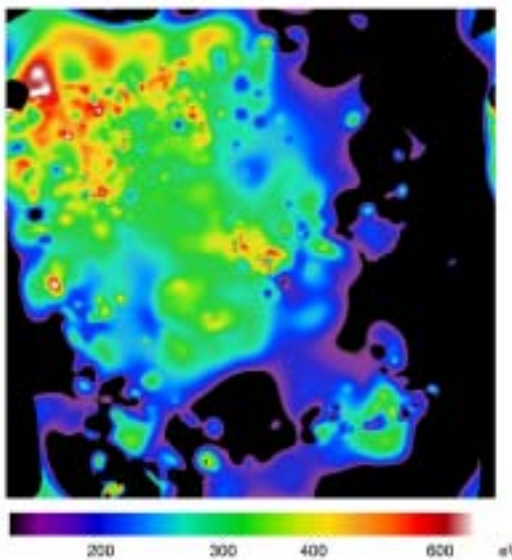


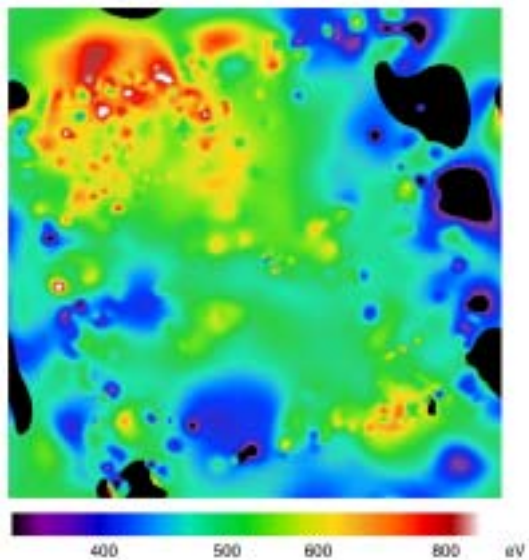
Fe Kα “neutral”

(E ~ 6.4 keV)

S Heα + Lyα

(E ~ 2.5 keV)





Si Heα

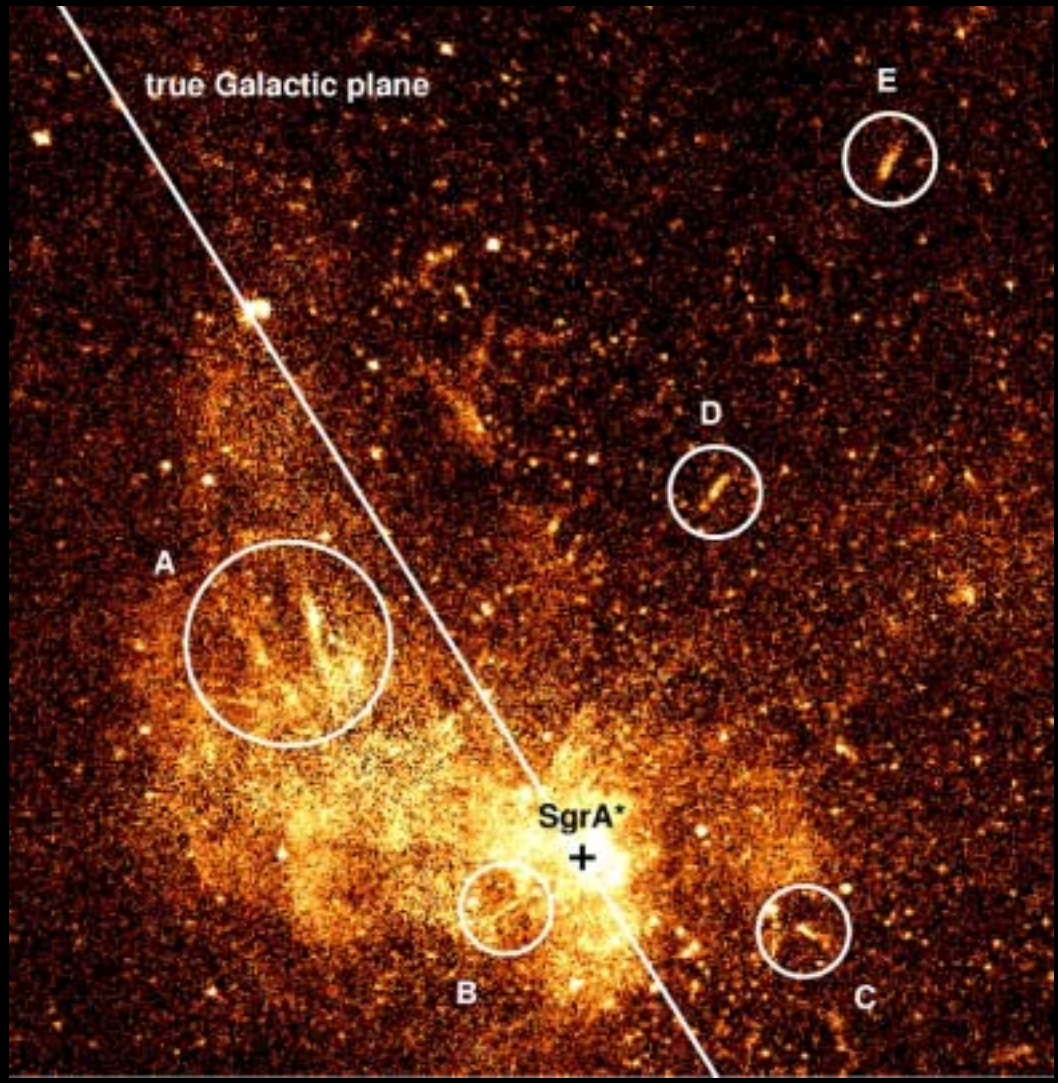
(E ~ 1.8 keV)

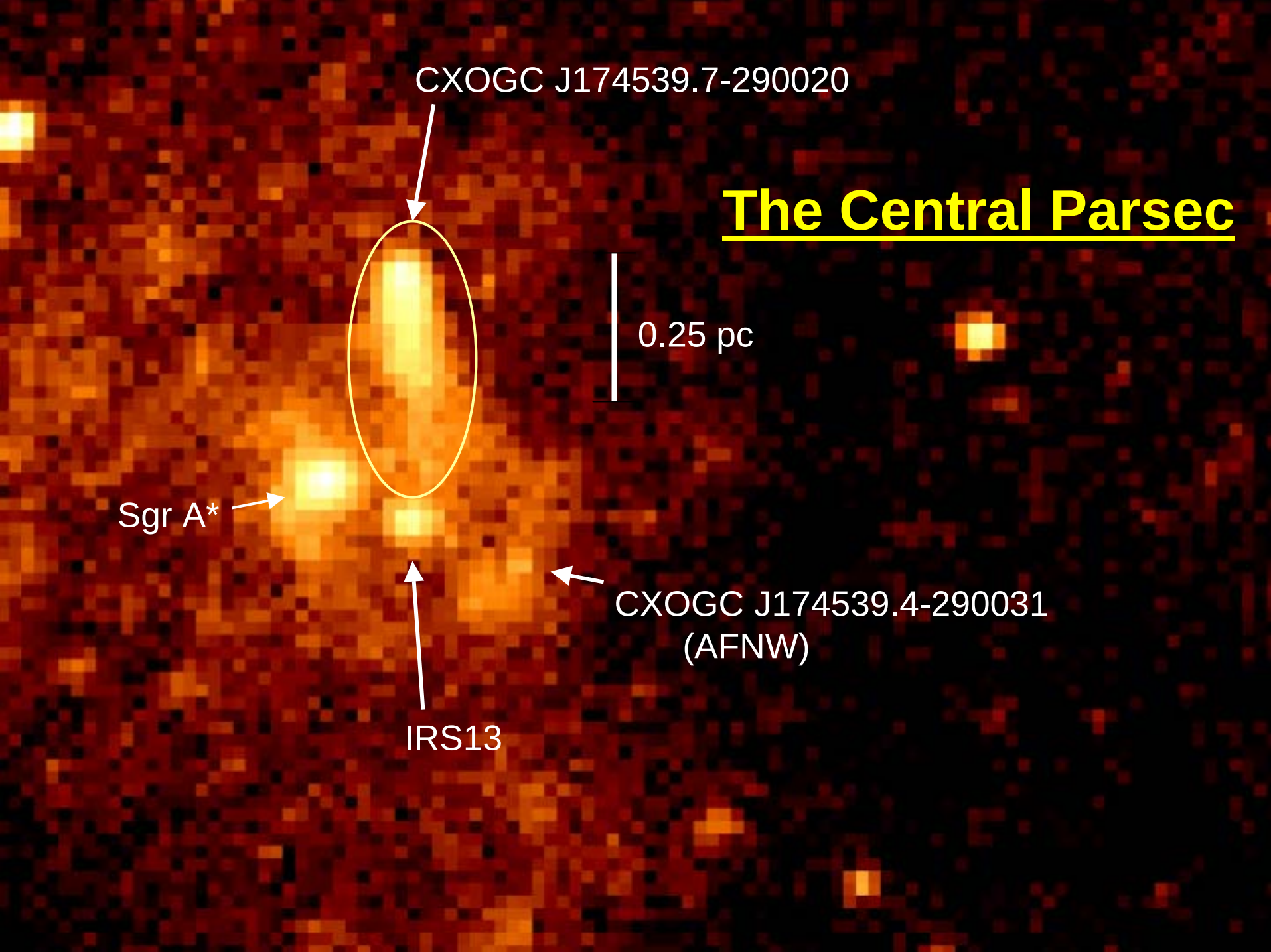
Park et al. (2003), submitted to ApJ

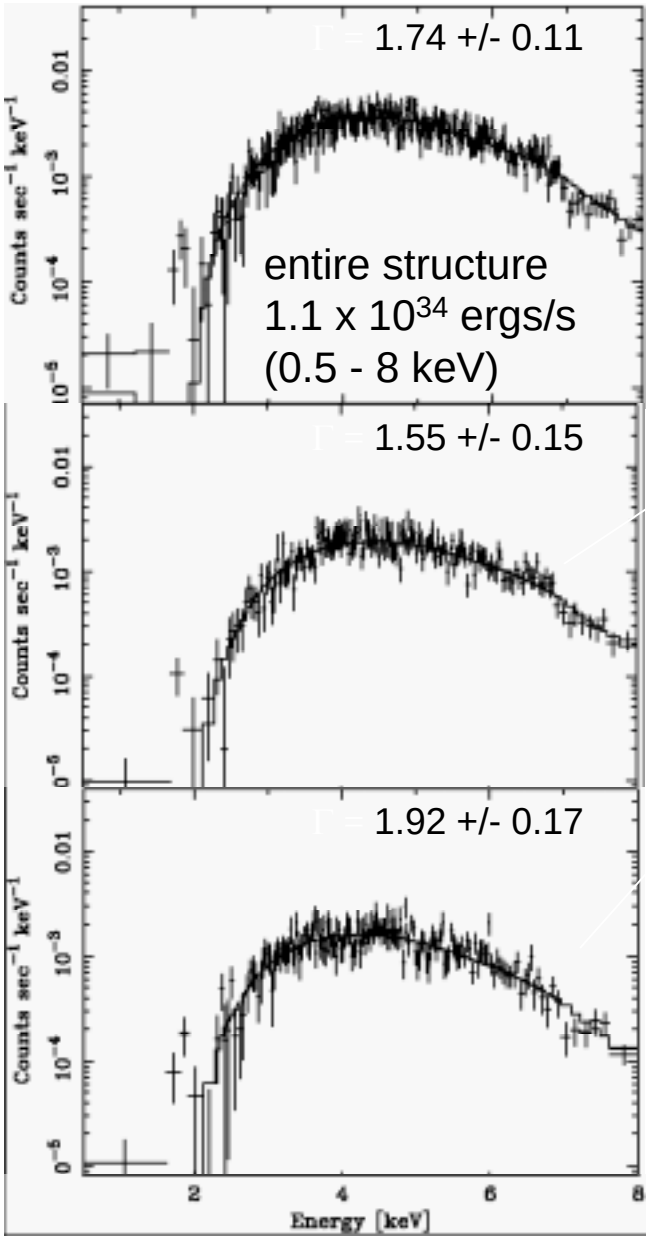
Galactic Center Bipolar Lobes

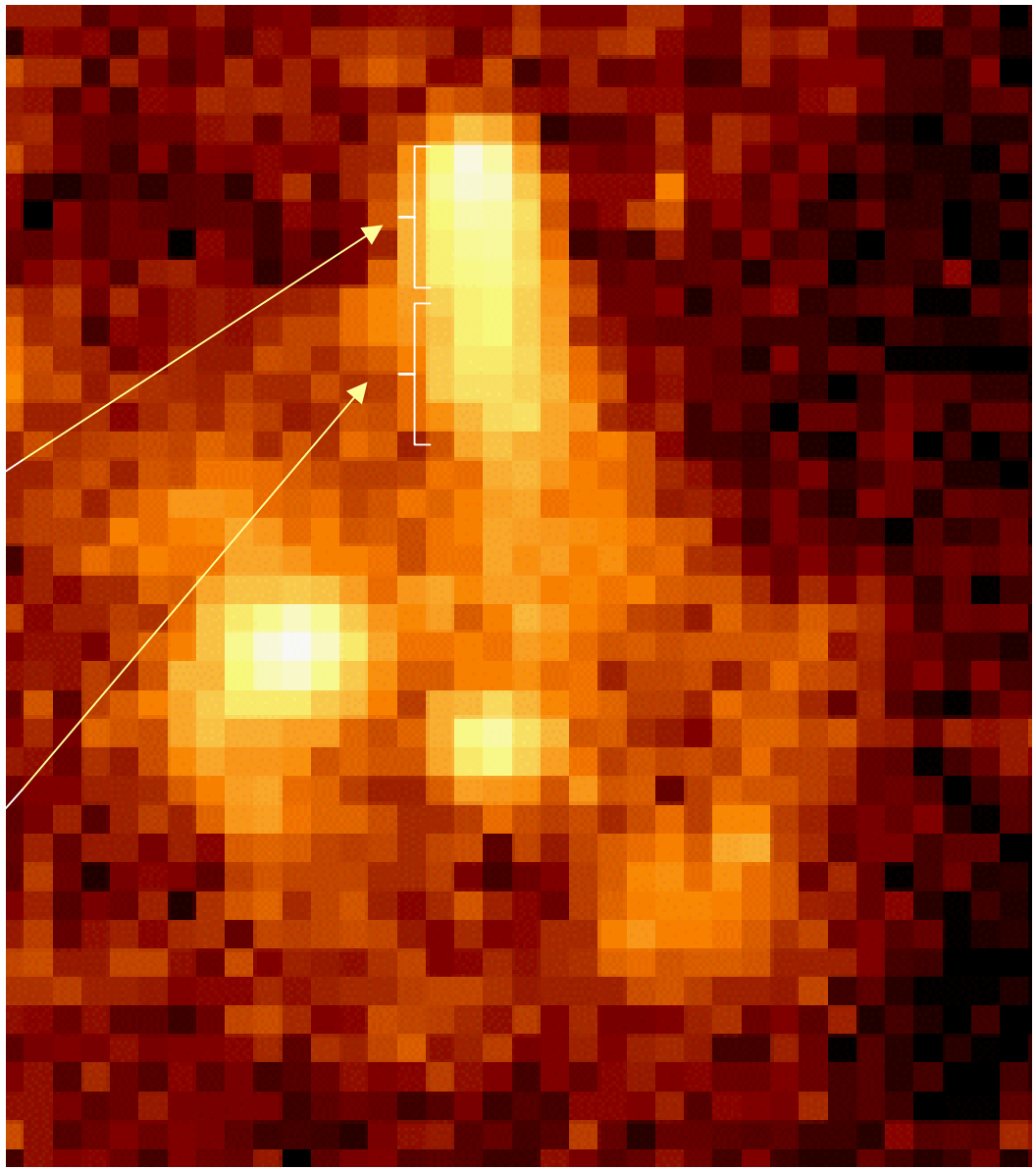
- Lobe material distributed differently than “hot” (6.7 keV) and fluorescent “neutral” (6.4 keV) Fe
- Emission grows in intensity and size perpendicular to Galactic plane toward lower energies
- $T_e \sim 2 \times 10^7$ K
- $n_e \sim 1$ cm^{-3}
- Separate lumps may indicate separate episodes of activity spaced by 2000–5000 yr
- Timescale for outer portions to flow from Sgr A*: 10^4 yr (v_{out}/1000 km s^{-1})
- Mass per blob ~ 1 M_{sun}
- Origin: Sgr A* or star formation in central parsec?

X-ray Features in the Vicinity of the Sgr A Radio Complex

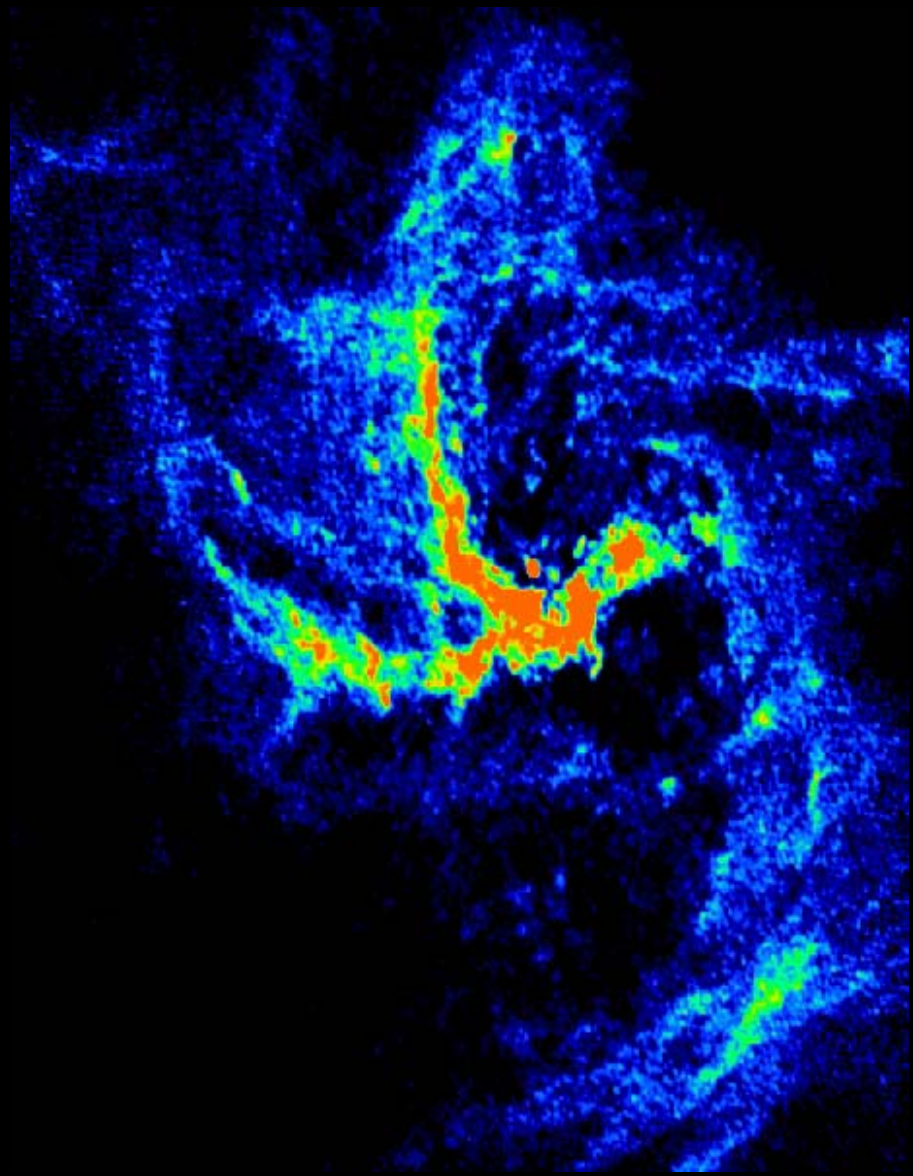



CXOGC J174539.7-290020
The Central Parsec
0.25 pc
Sgr A*
CXOGC J174539.4-290031
(AFNW)
IRS13

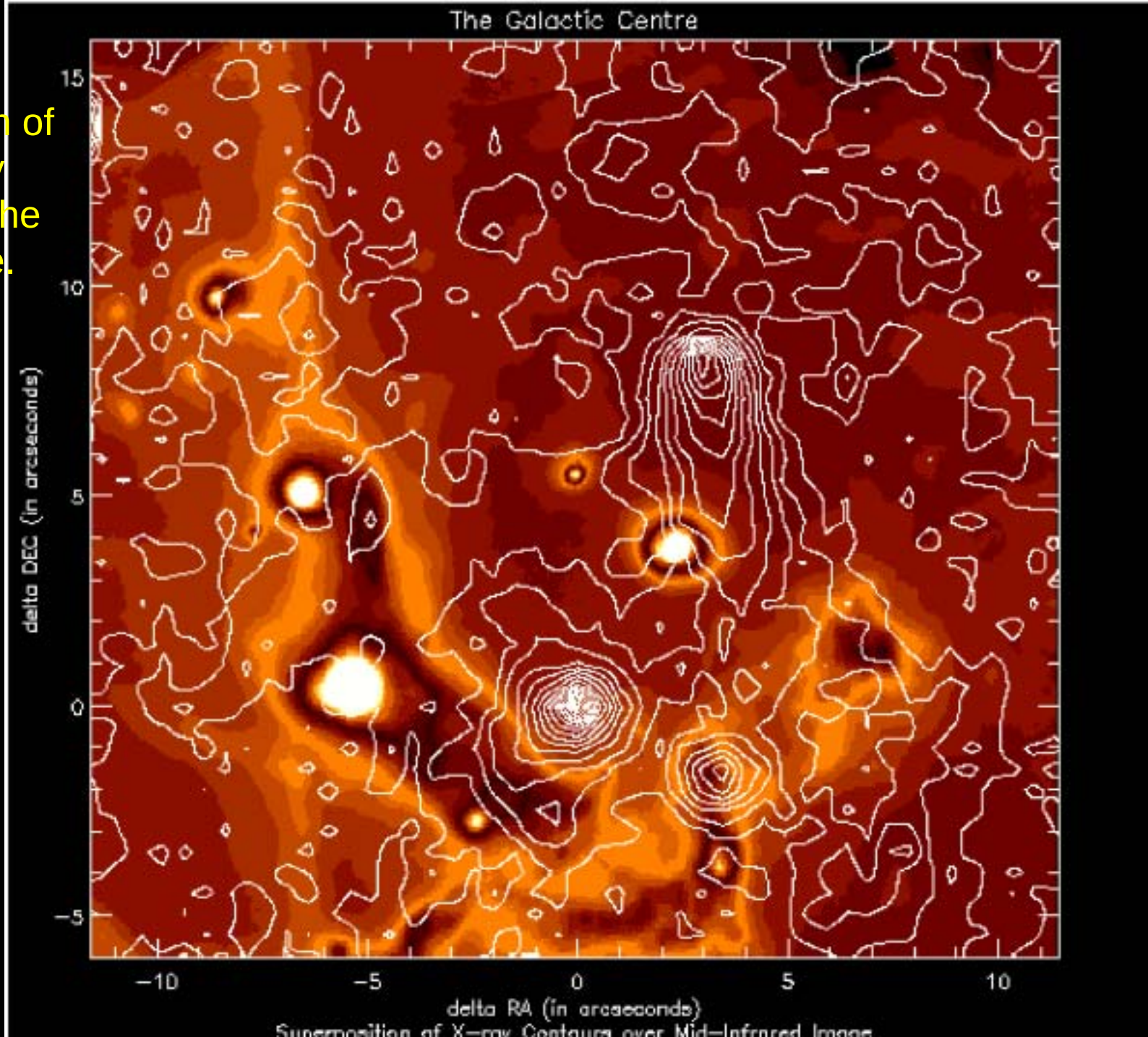

Γ = 1.74 +/- 0.11
entire structure
1.1 x 10^34 ergs/s
(0.5 - 8 keV)
Γ = 1.55 +/- 0.15
Γ = 1.92 +/- 0.17
Counts sec^-1 keV^-1
Energy [keV]



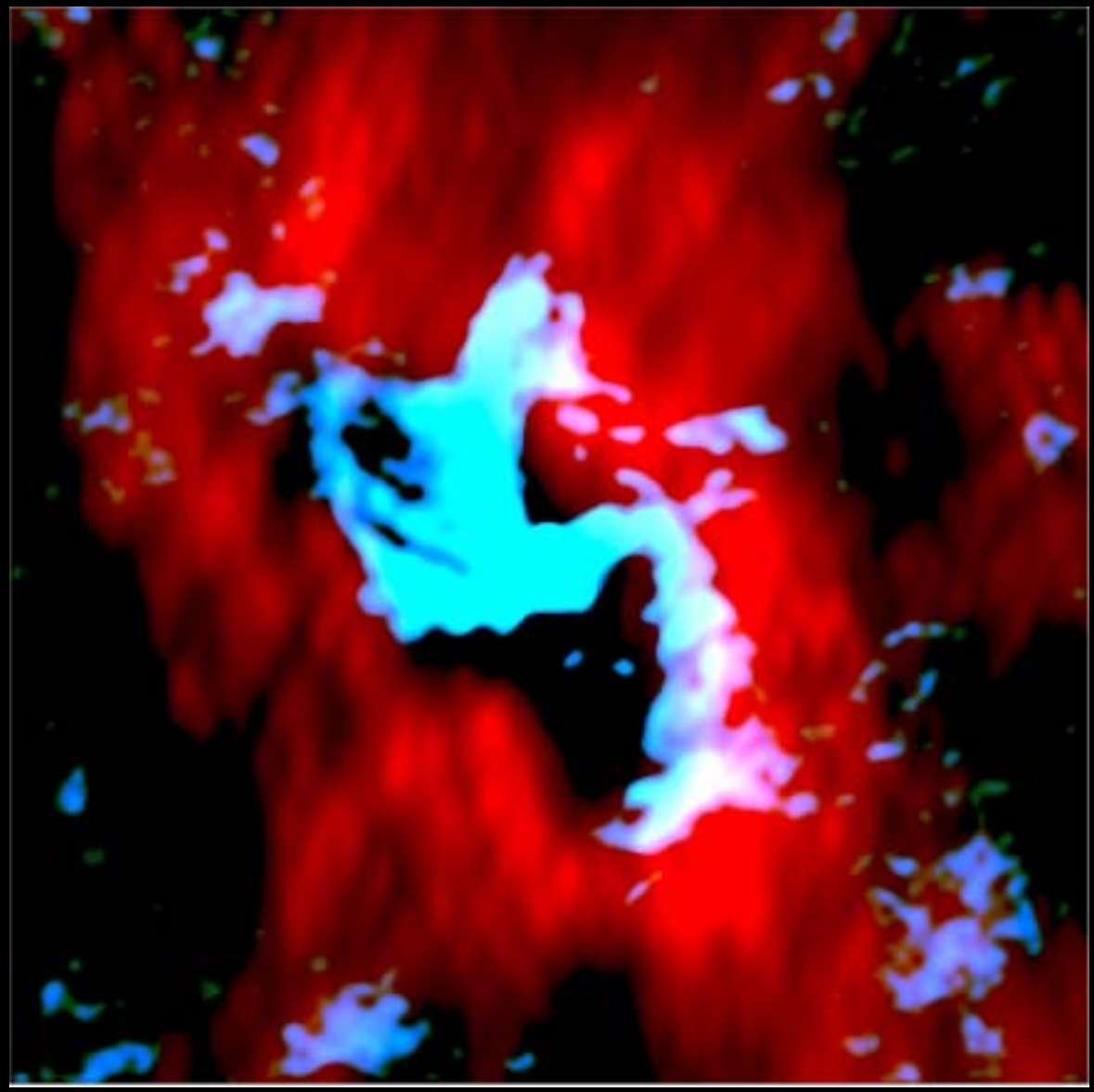
Radio Image of the Sgr A West Minispiral



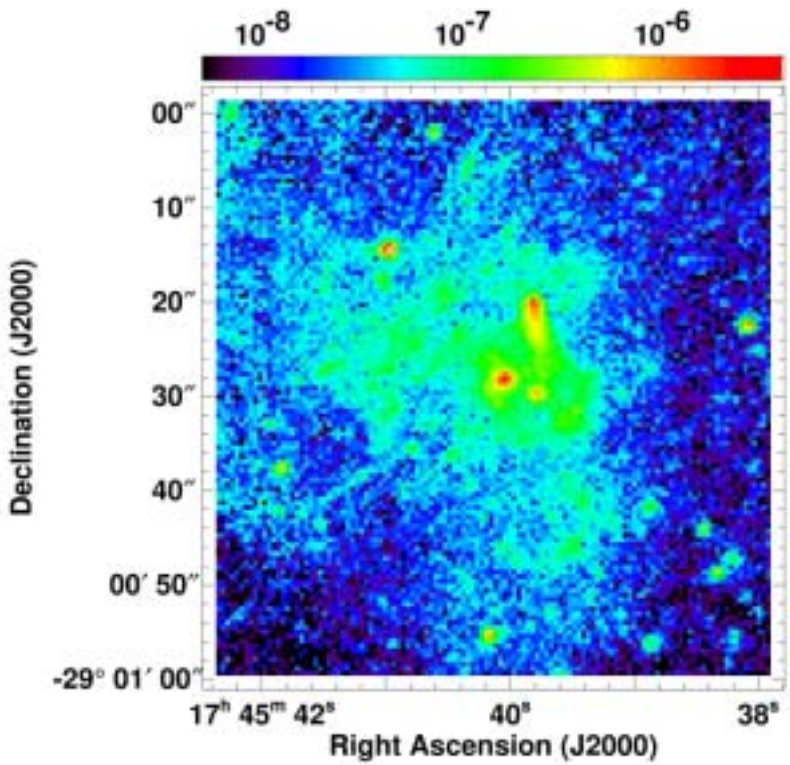
Superposition of 2-8 keV x-ray contours on the mid-IR image.

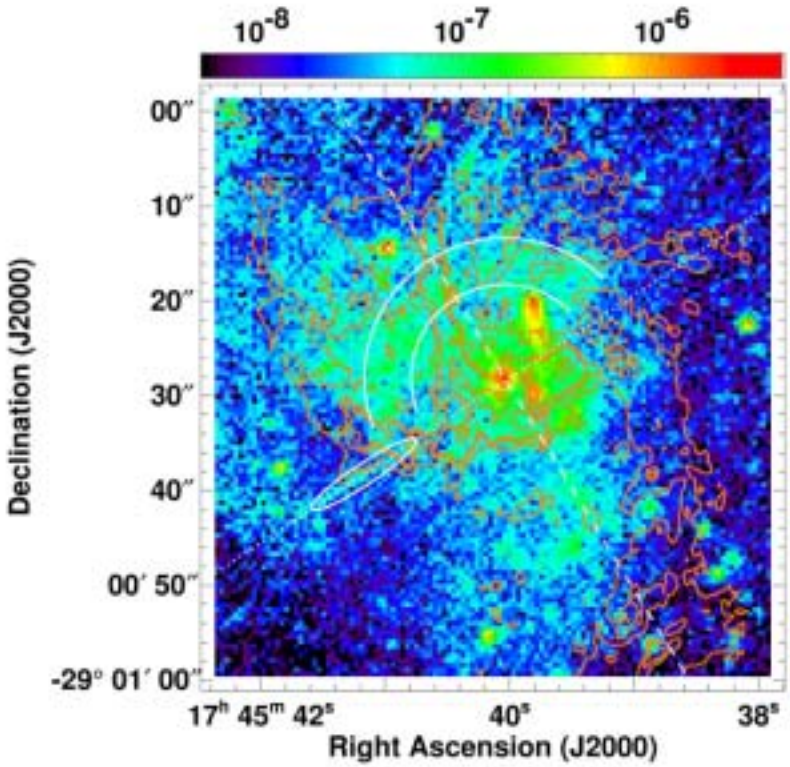


Radio Image of Sgr A West and Circumnuclear Disk

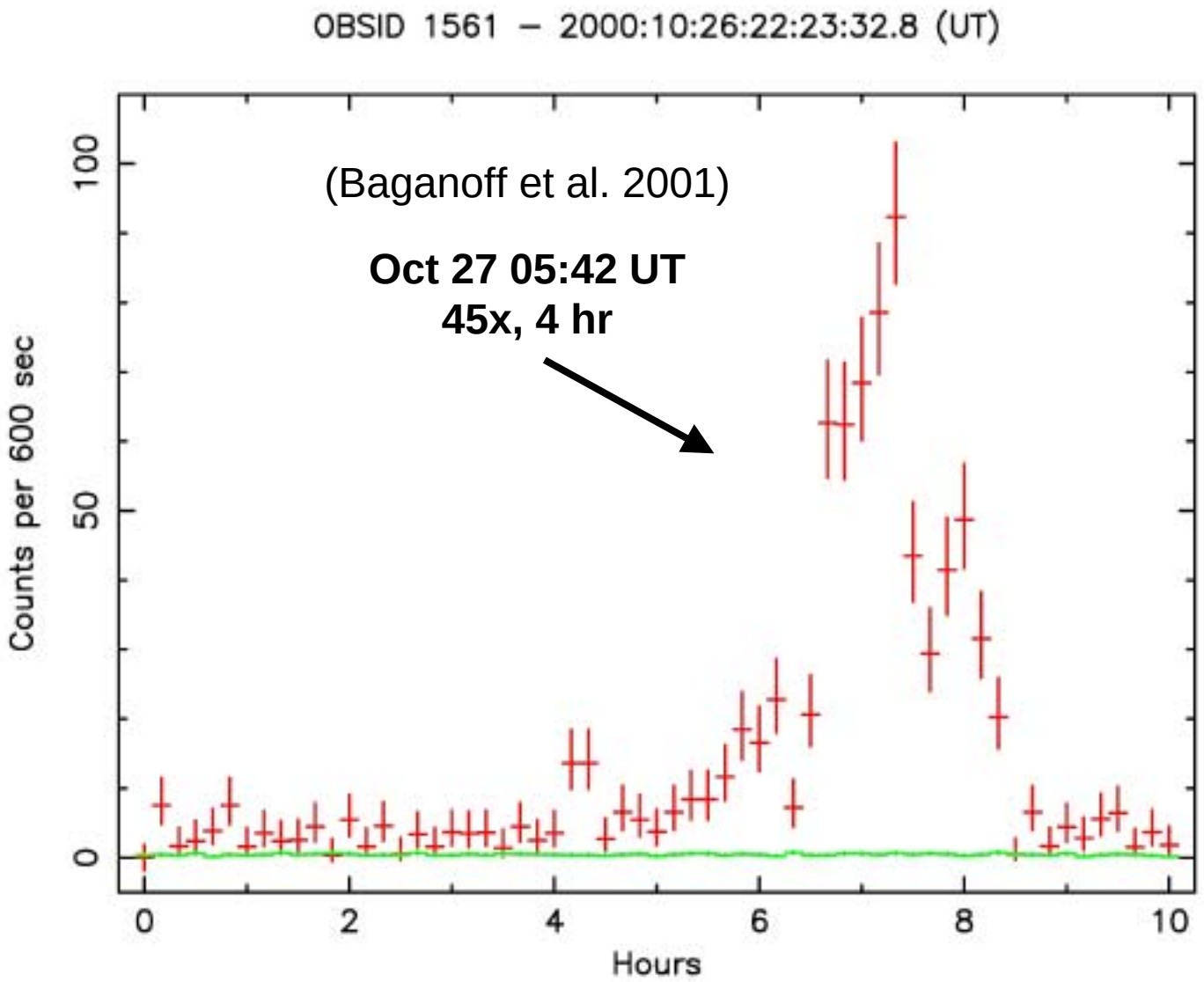


X-ray Image and 6 cm Contours of Sgr A West

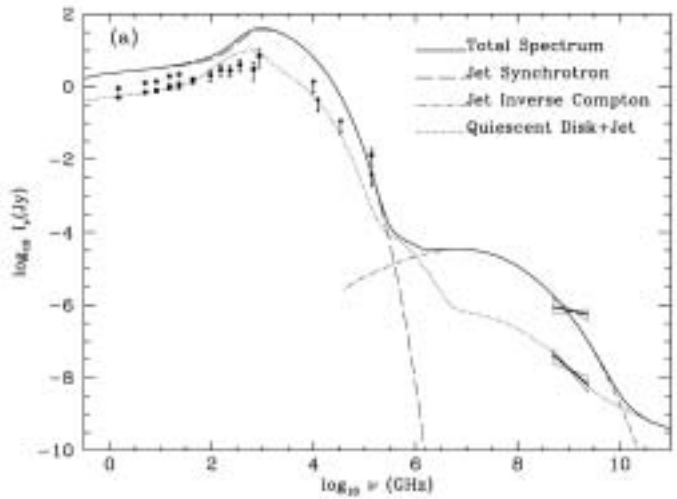


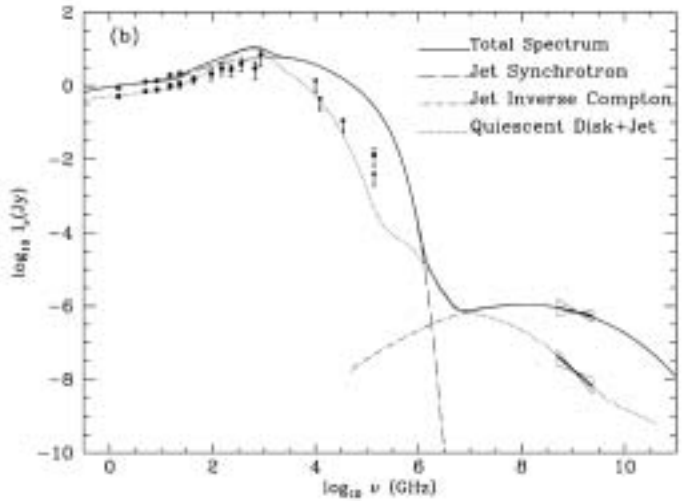


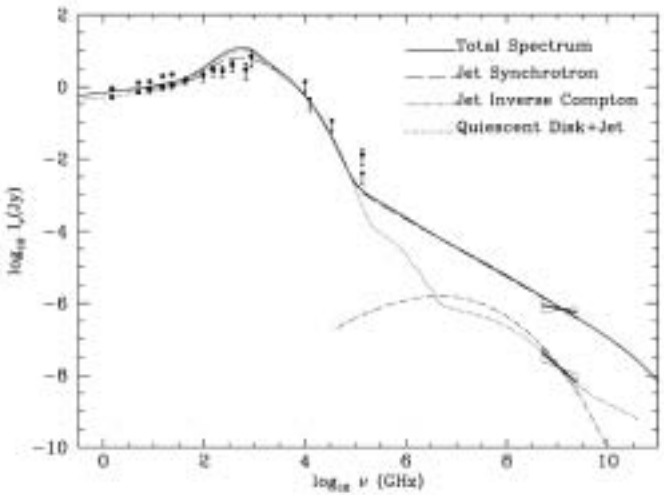
2000 October 26-27



Jet Models - Markoff et al. 2001

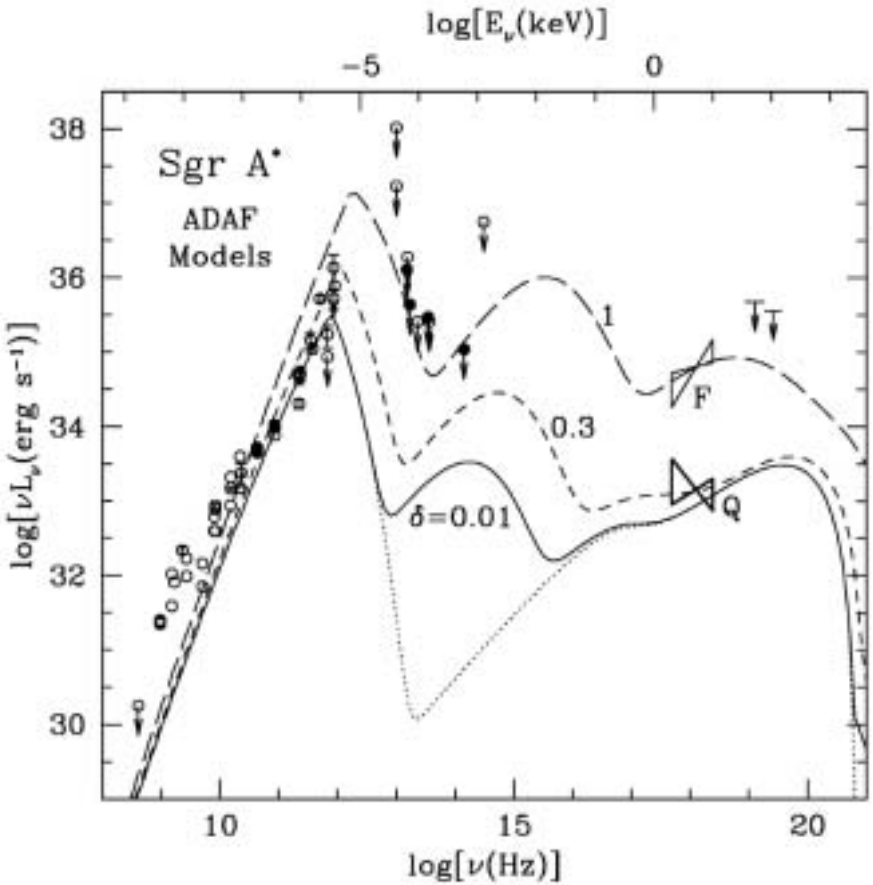






Some models predict large mm or IR variations during X-ray flares, while others do not

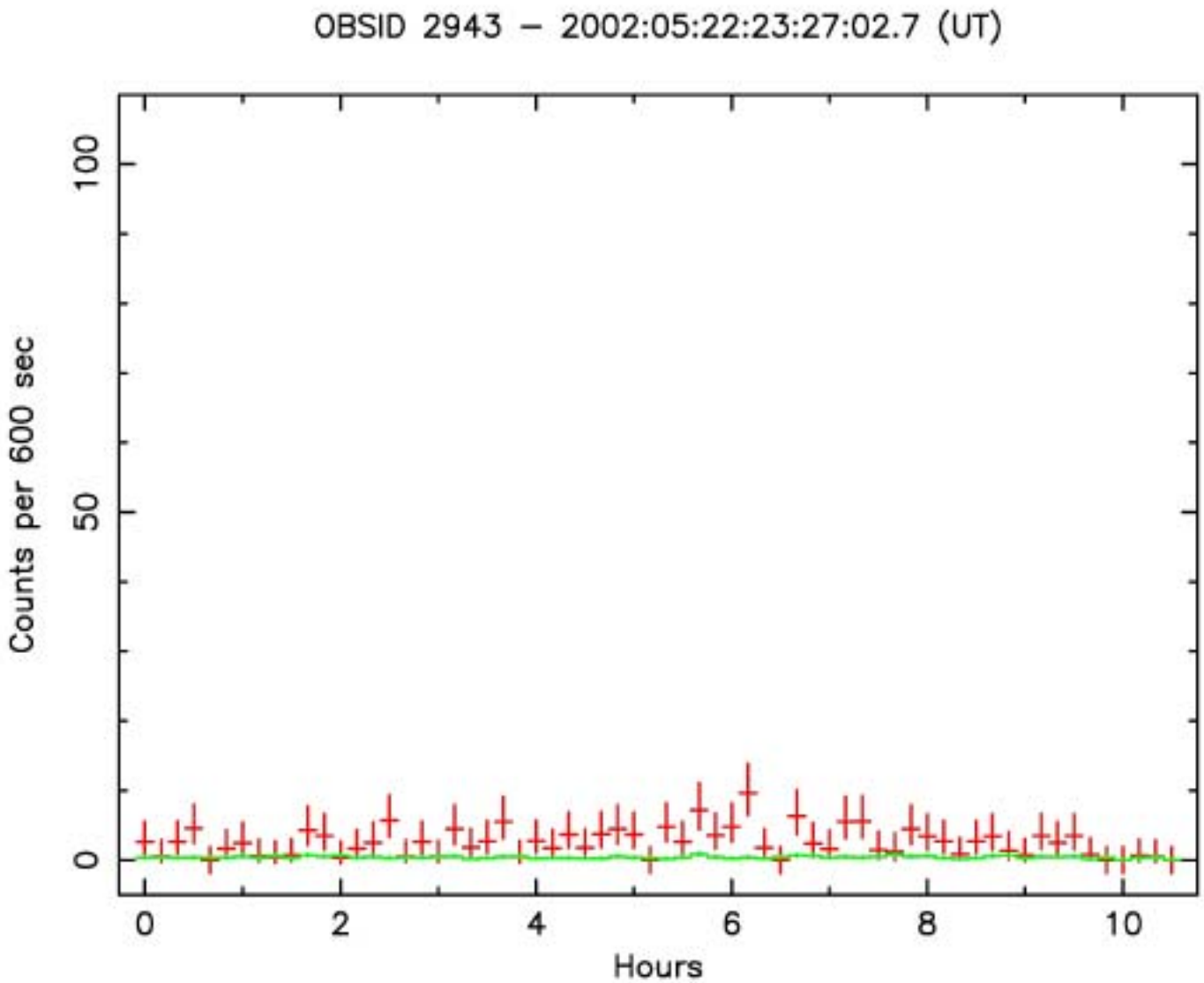
ADAF Model – Narayan 2002



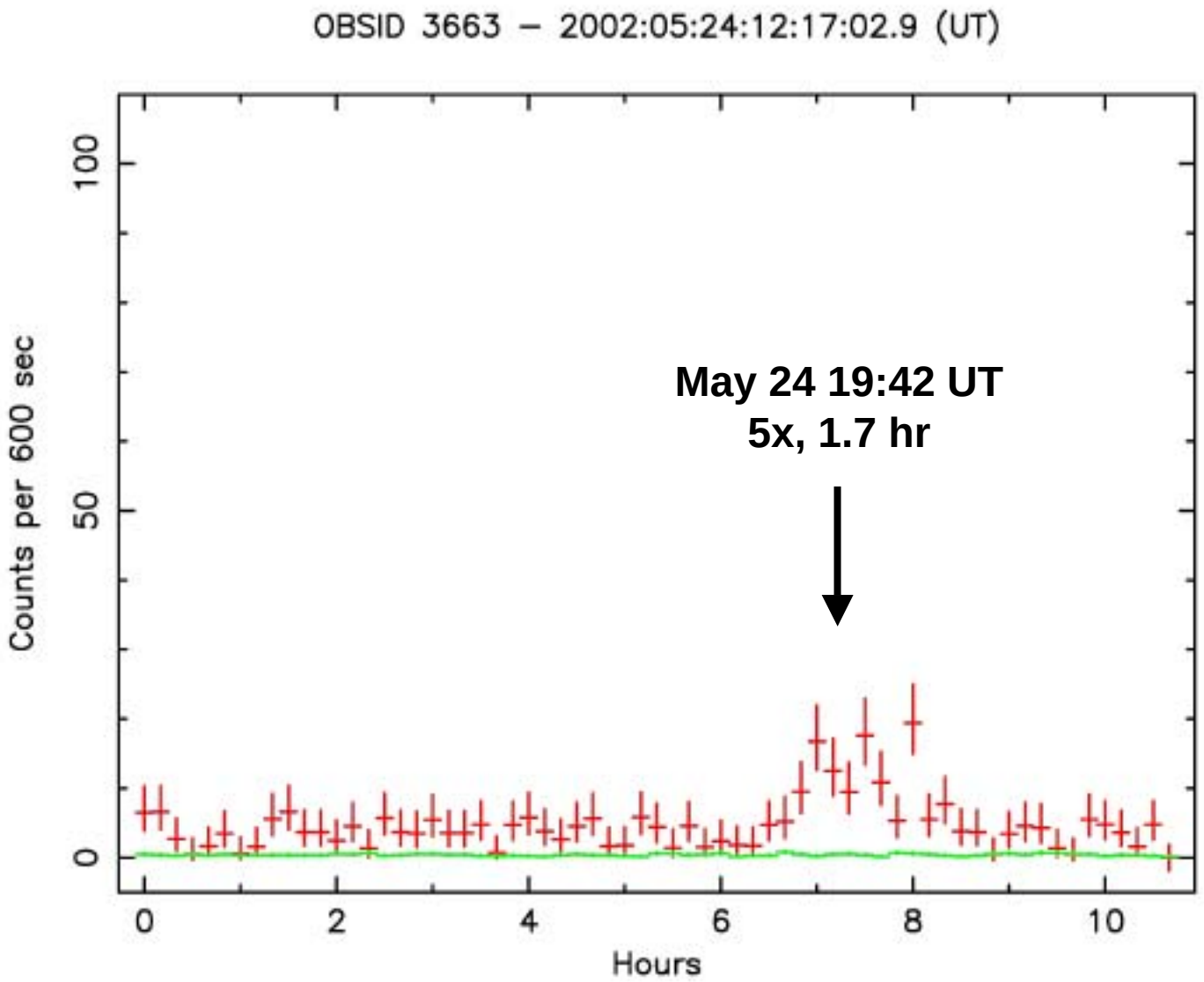
Observatories Participating in Sgr A* Monitoring Campaign

- Chandra (12–62 nm)
- Keck (2 & 10 μm)
- Very Large Telescope (3–5 μm)
- Magellan (10 μm)
- Submillimeter Array (1.3 mm)
- Caltech OVRO Millimeter Array (3 mm)
- Australia Telescope Compact Array (3 mm)
- Very Large Baseline Array (7 mm)
- Very Large Array (7mm, 1.3 cm, 2 cm)

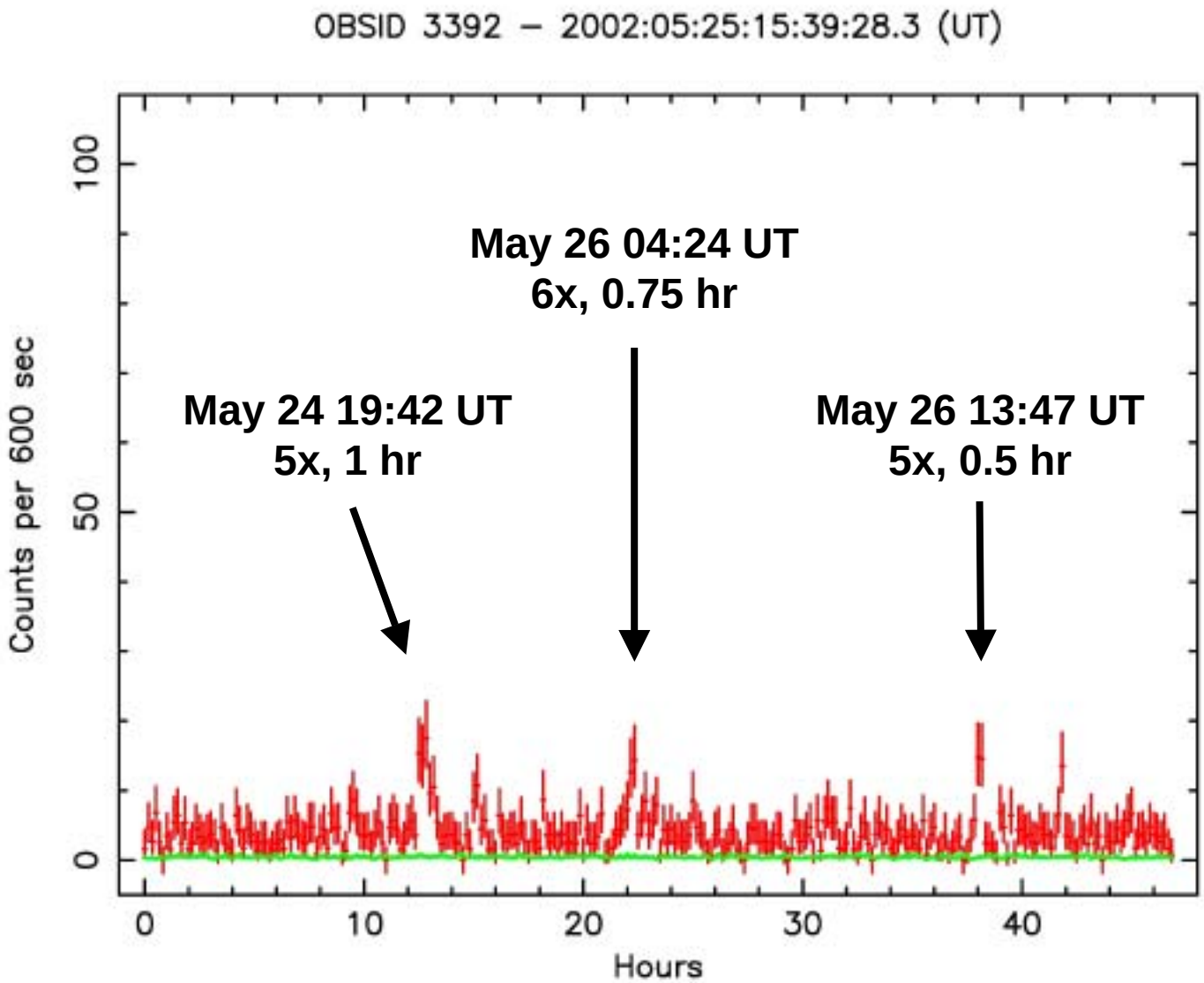
2002 May 22-23 – Orbit 1, Part 1



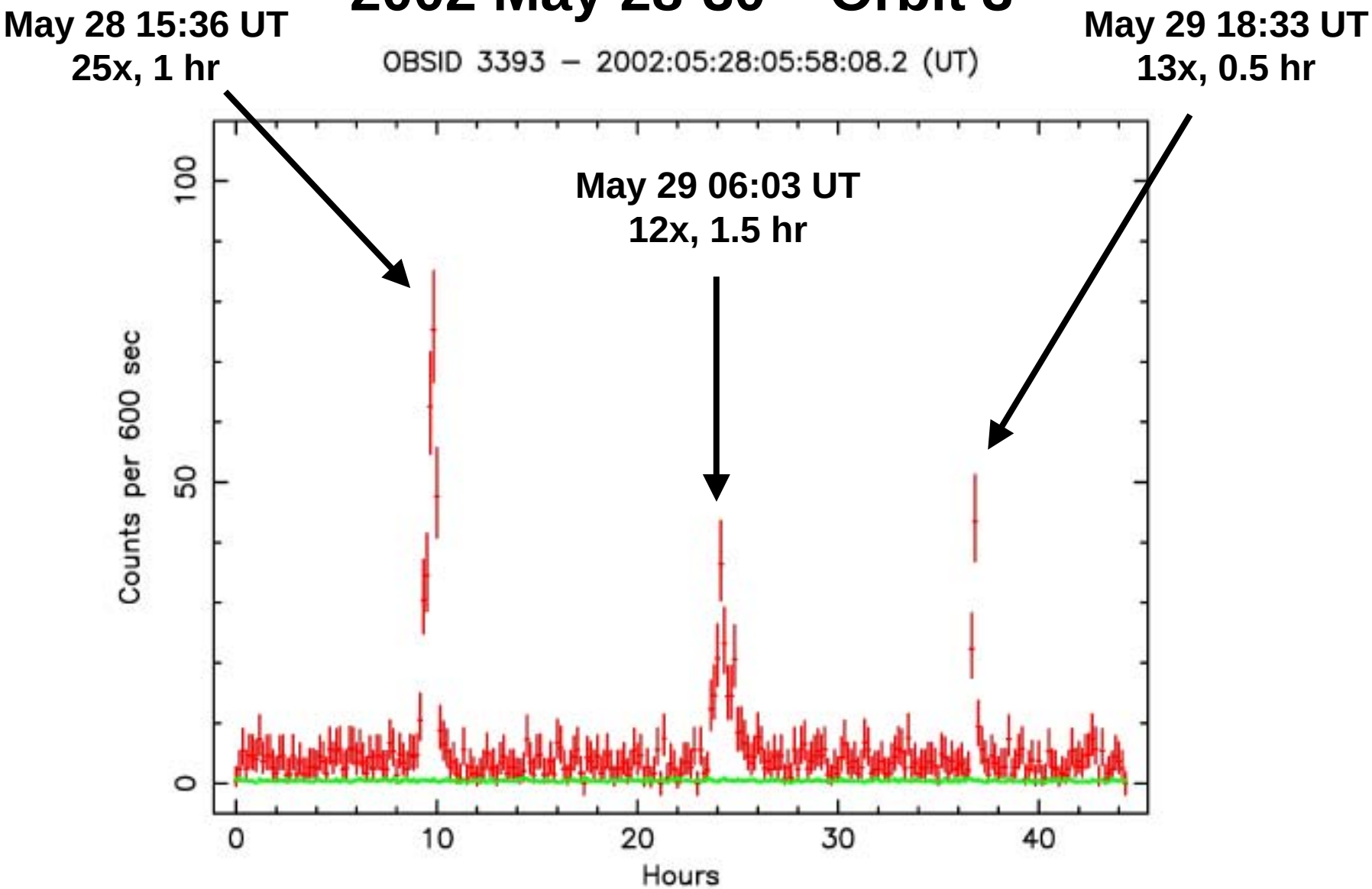
2002 May 24 – Orbit 1, Part 2



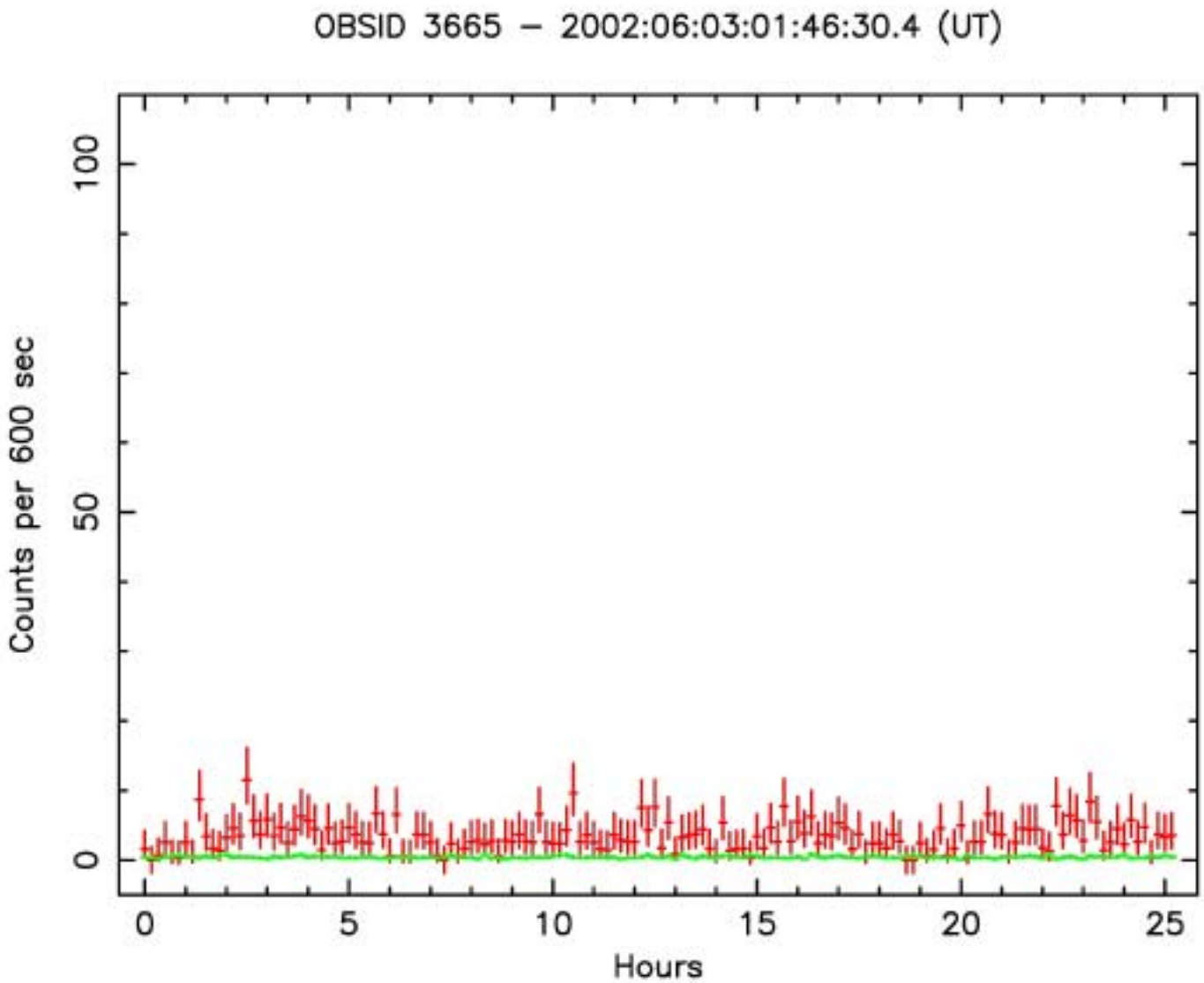
2002 May 25-27 – Orbit 2



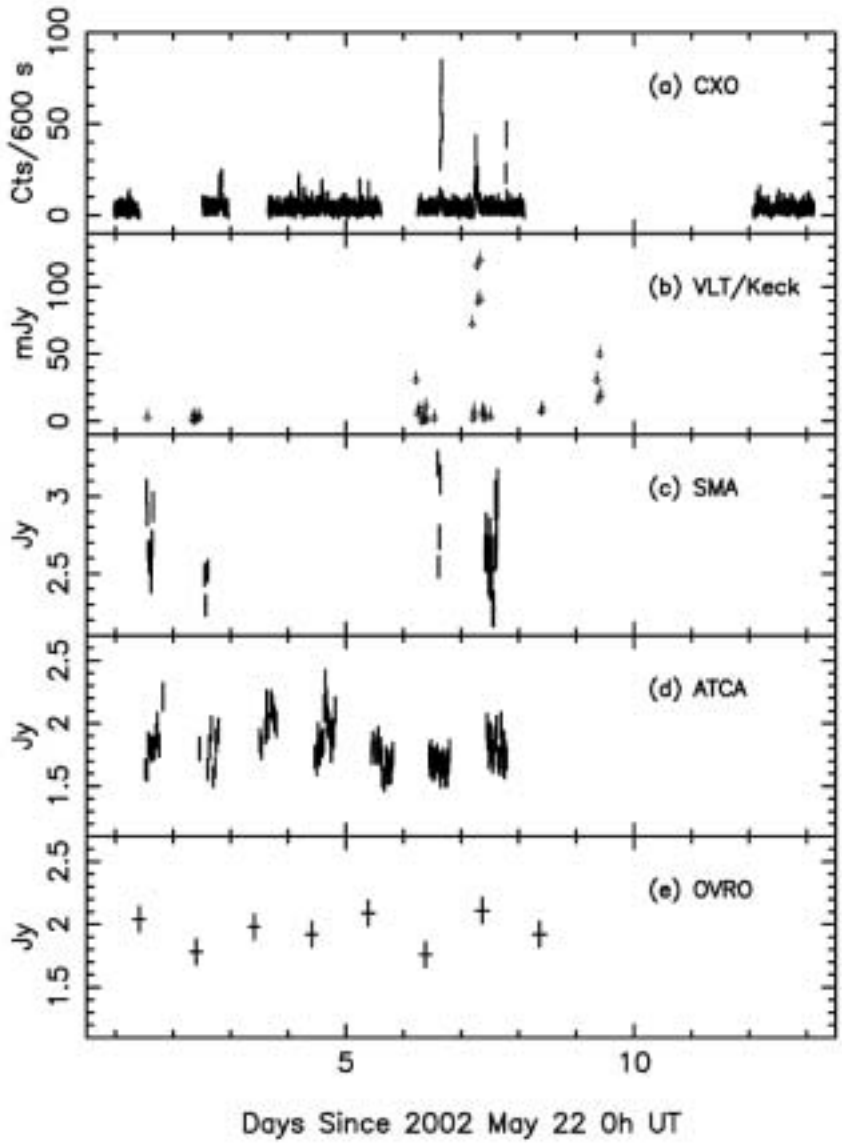
2002 May 28-30 – Orbit 3



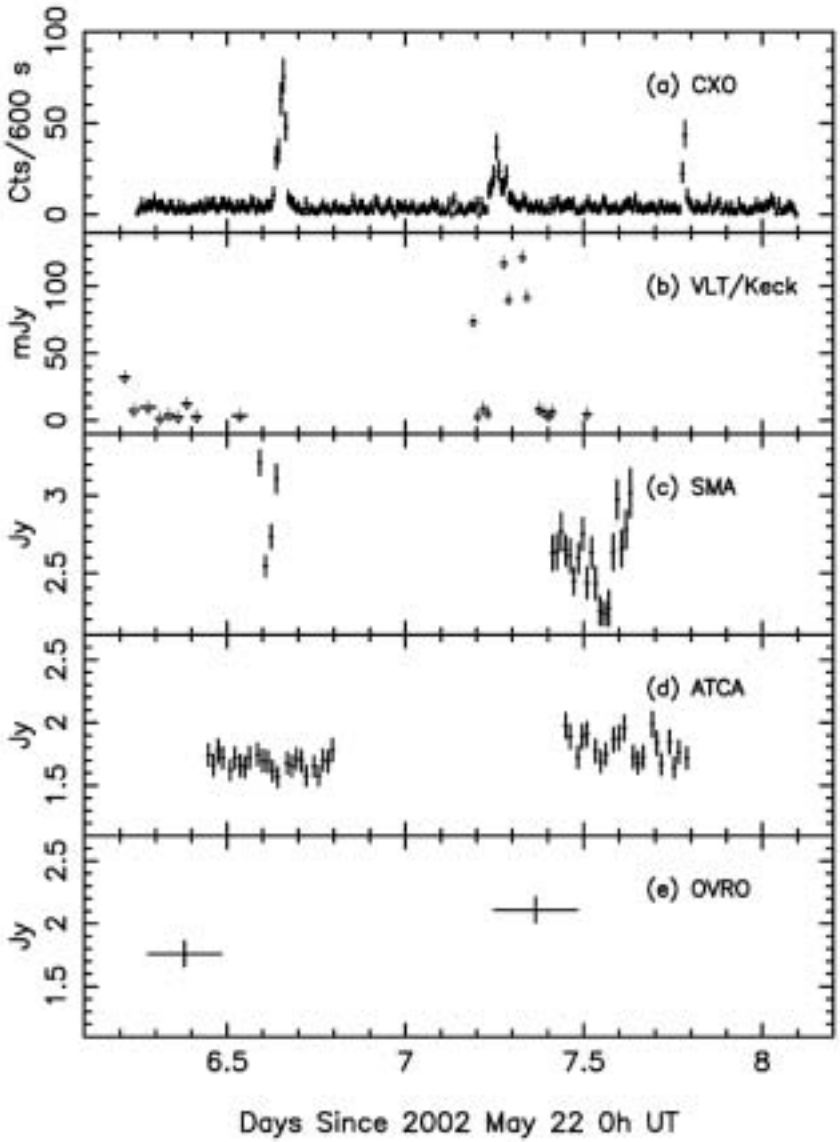
2002 June 3-4 – Orbit 5



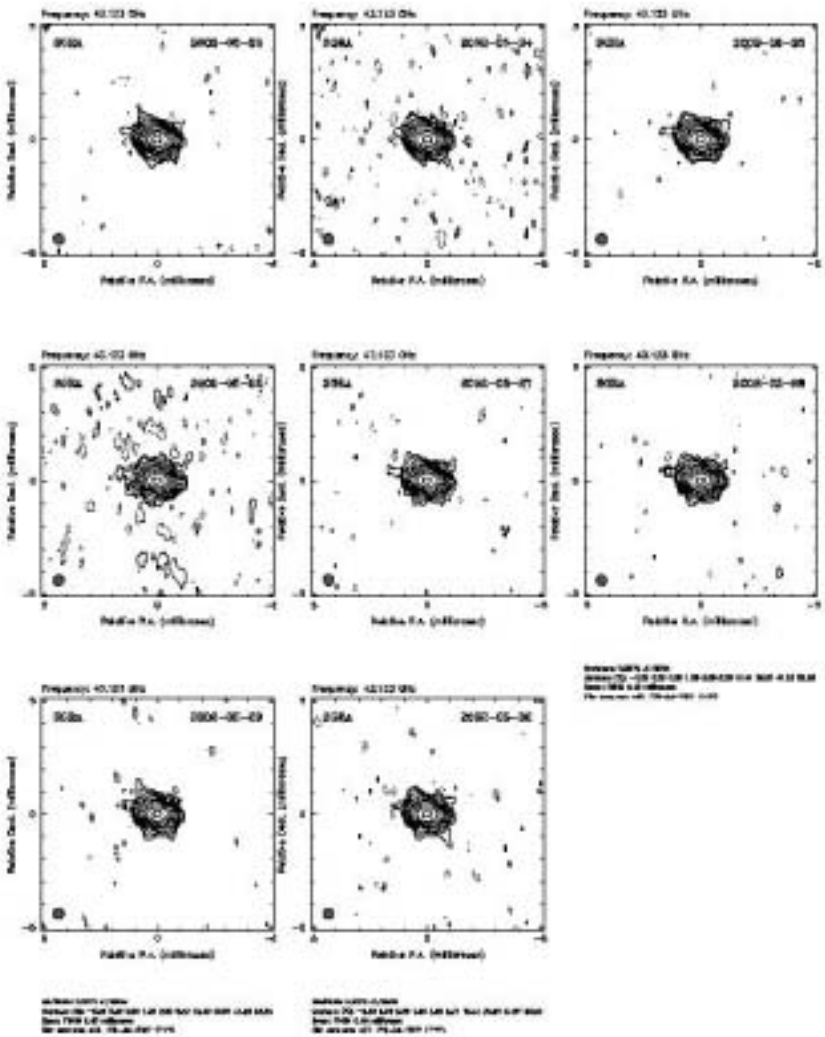
Sgr A* Multiwavlength Monitoring Campaign



Three Large X-ray Flares from Sgr A*



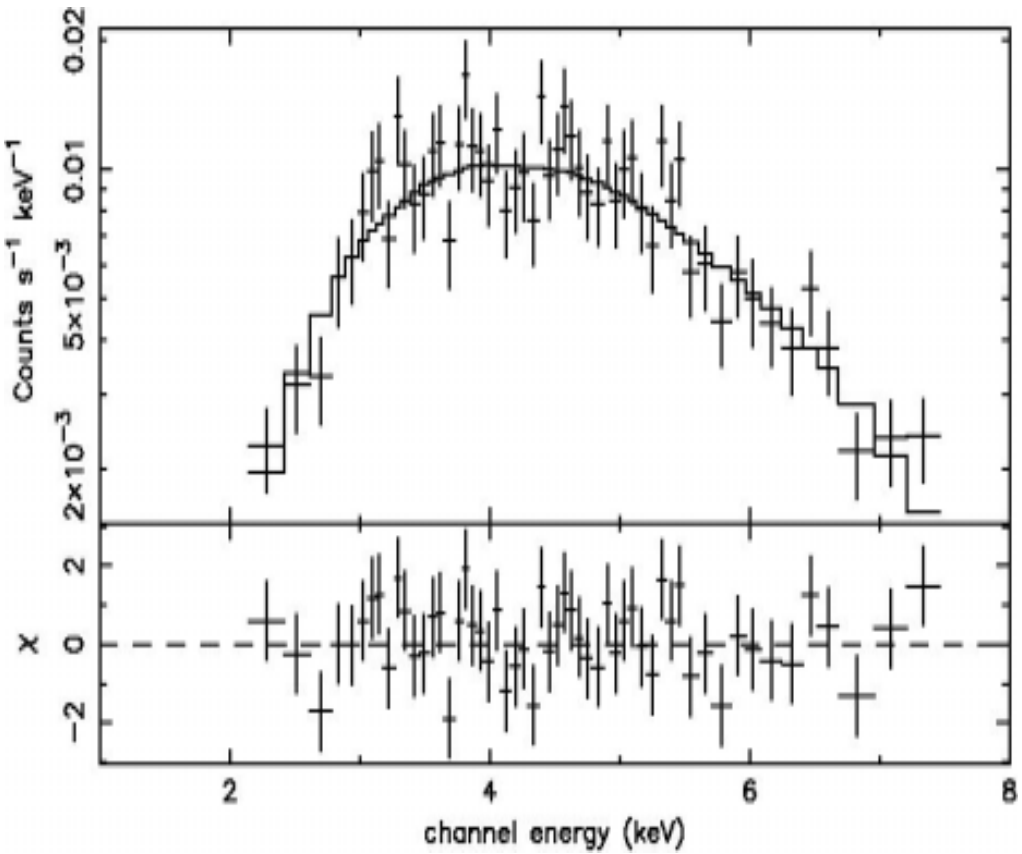
Very Long Baseline Array – 7 mm



- No significant flux variability detected
- Upper limit about 30%
- No extended structure appeared
- Upper limit about 10 mJy

Integrated X-ray Spectrum of Sgr A* During Flares

Model: Absorbed, Dust-Scattered Power Law

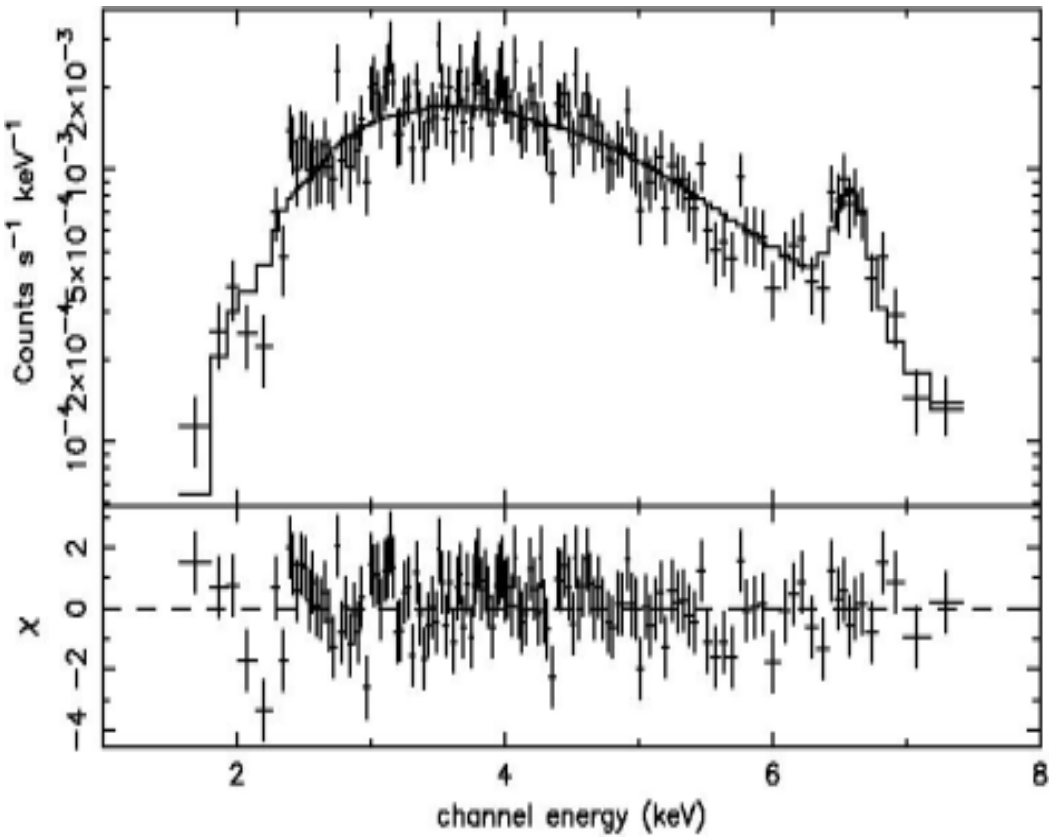


$N_H = 6.0 \times 10^{22}$ cm^{-2}
$\Gamma = 1.3$ (0.9-1.8)

$F_X = 1.6 \times 10^{-12}$ erg cm^{-2} s^{-1}
$L_X = 2.0 \times 10^{34}$ erg s^{-1}
D = 8 kpc

Integrated X-ray Spectrum of Sgr A* in Quiescence

Model: Absorbed, Dust-Scattered, Power Law Plus Line



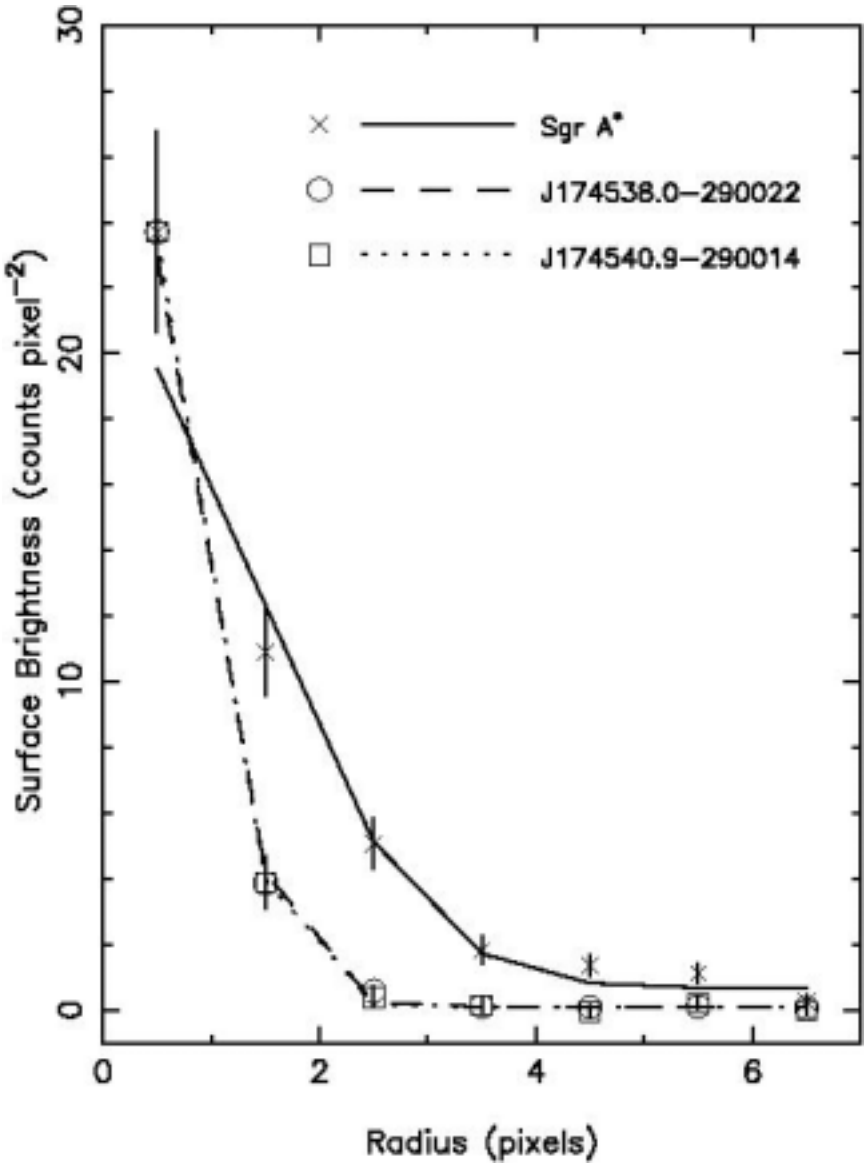
N_H = 5.9 x 10^{22} cm^{-2}
Γ = 2.4 (2.3-2.6)

E_{Fe} = 6.59 (6.54-6.64) keV
Line is narrow and NIE

F_X = 1.8 x 10^{-13} erg cm^{-2} s^{-1}
L_X = 1.4 x 10^{33} erg s^{-1}
D = 8 kpc

$\langle L_F \rangle$ / $\langle L_Q \rangle$ = 14.0

X-ray Emission at Sgr A* is Extended



- Intrinsic size of emission at Sgr A* is about 1.4 arcsec (FWHM)
- Consistent with Bondi accretion radius for a 3×10^6 solar-mass black hole
- Is emission from a hot accretion flow or from stars in the central cluster?

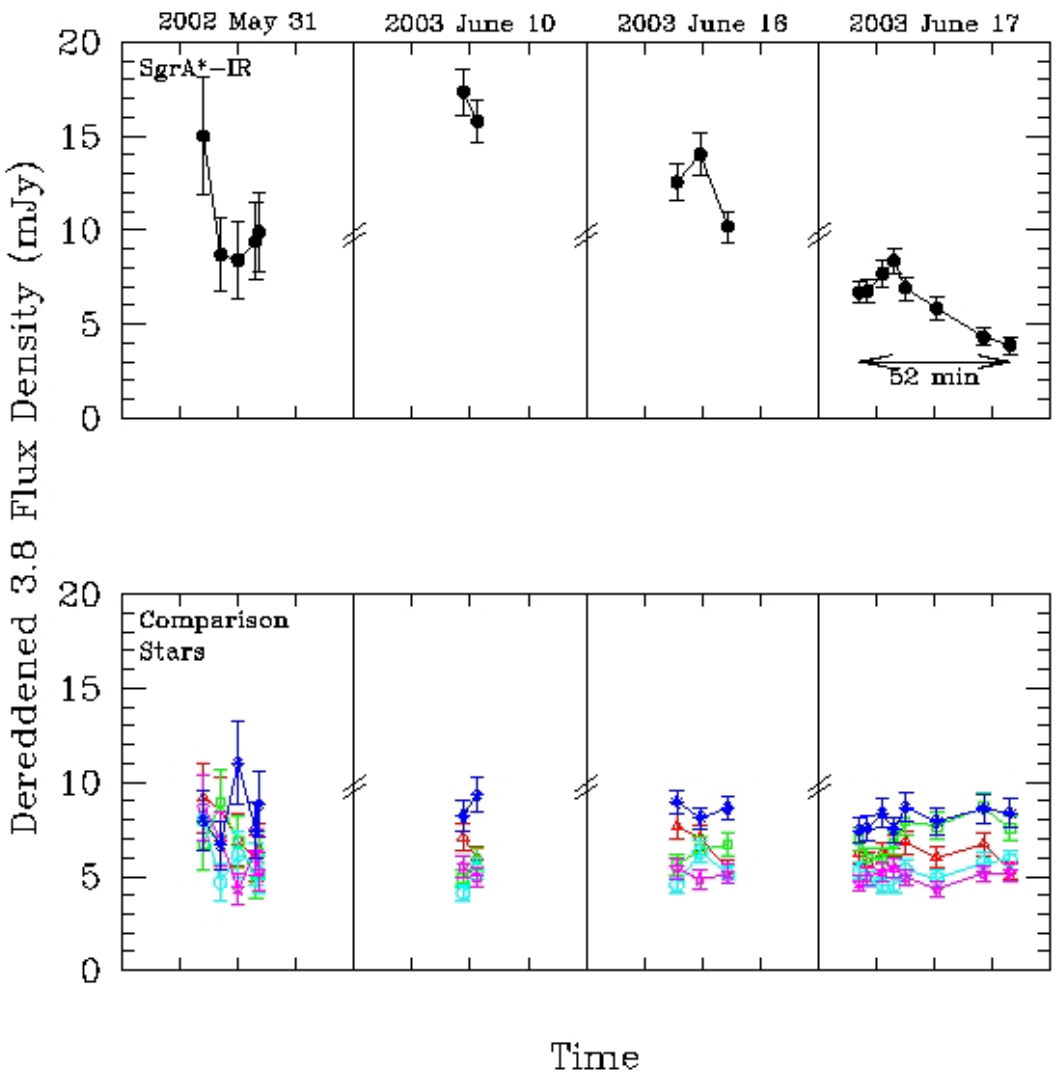
Summary - Sgr A* Flares

- Chandra observed Sgr A* for 139 hr over a two-week period in late May to early June 2002
- **3 X-ray flares with amplitudes >10x detected in a 28-hr period!**
- 4 X-ray flares with amplitudes ~5x detected in addition
- **“Factor-of-10” flares occur about once every other day, on average**
- Typical flare duration is about 1 hr (0.5-4 hr)
- **Frequent, large-amplitude, short-duration flaring** behavior of Sgr A* is **unique** among supermassive black holes!
- Probably selection effect: **flares too faint to detect in other galaxies**
- Behavior **inconsistent** with X-ray binaries and **not seen** from any of the other **>2,300** X-ray point sources in the field
- **Strong evidence** that X-ray flaring source **is** the Milky Way’s central, supermassive black hole!

Summary – Sgr A* Flares (continued)

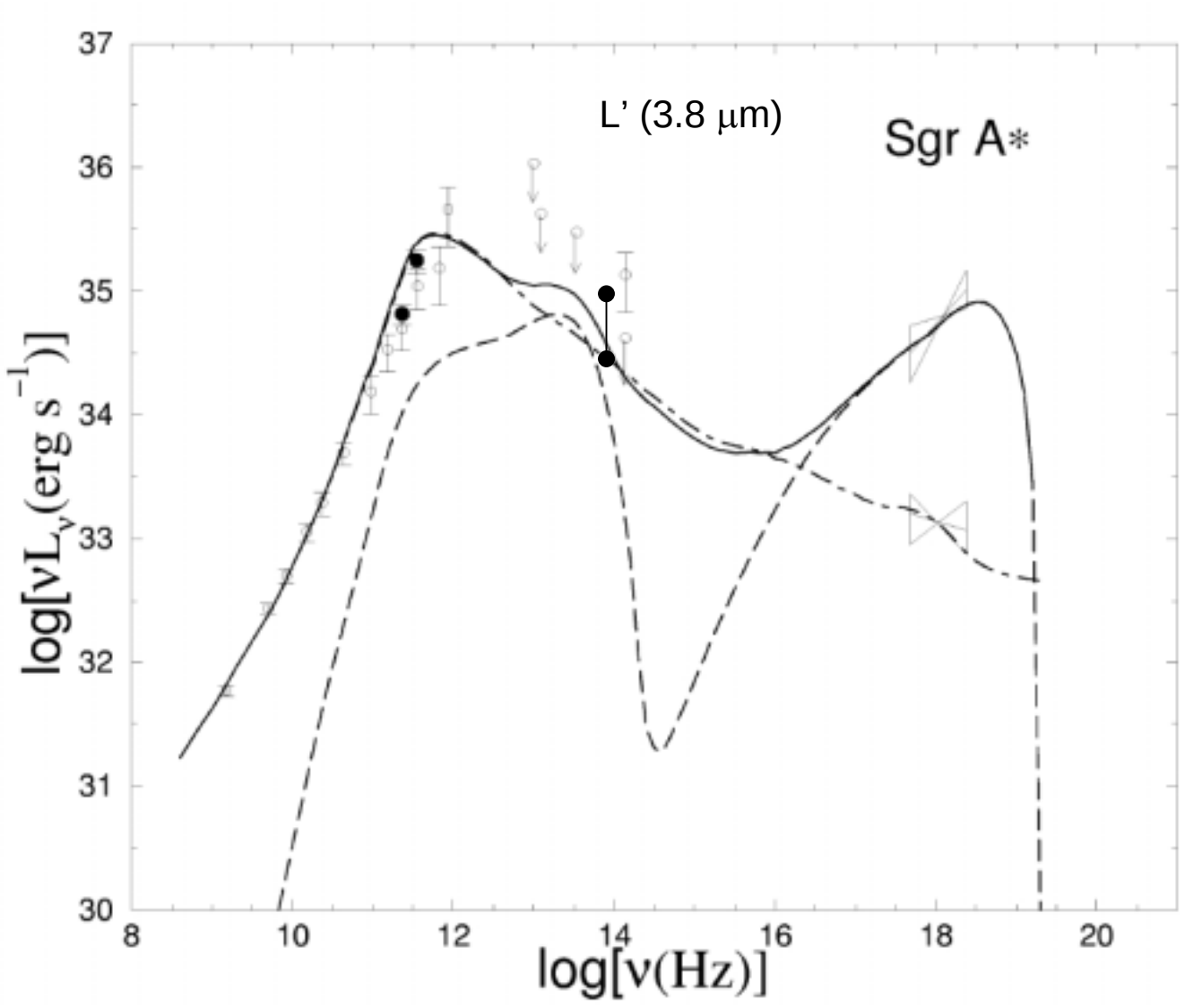
- **No factor-of-2 or larger flares seen at longer wavelengths**
- Some evidence for variations at tens of percent level in millimeter band on timescales of hours to days seen – **upper limit currently about 50%**
- Efforts to improved calibration of millimeter data underway

Keck L' (3.8 μm) Lightcurves of Sgr A*

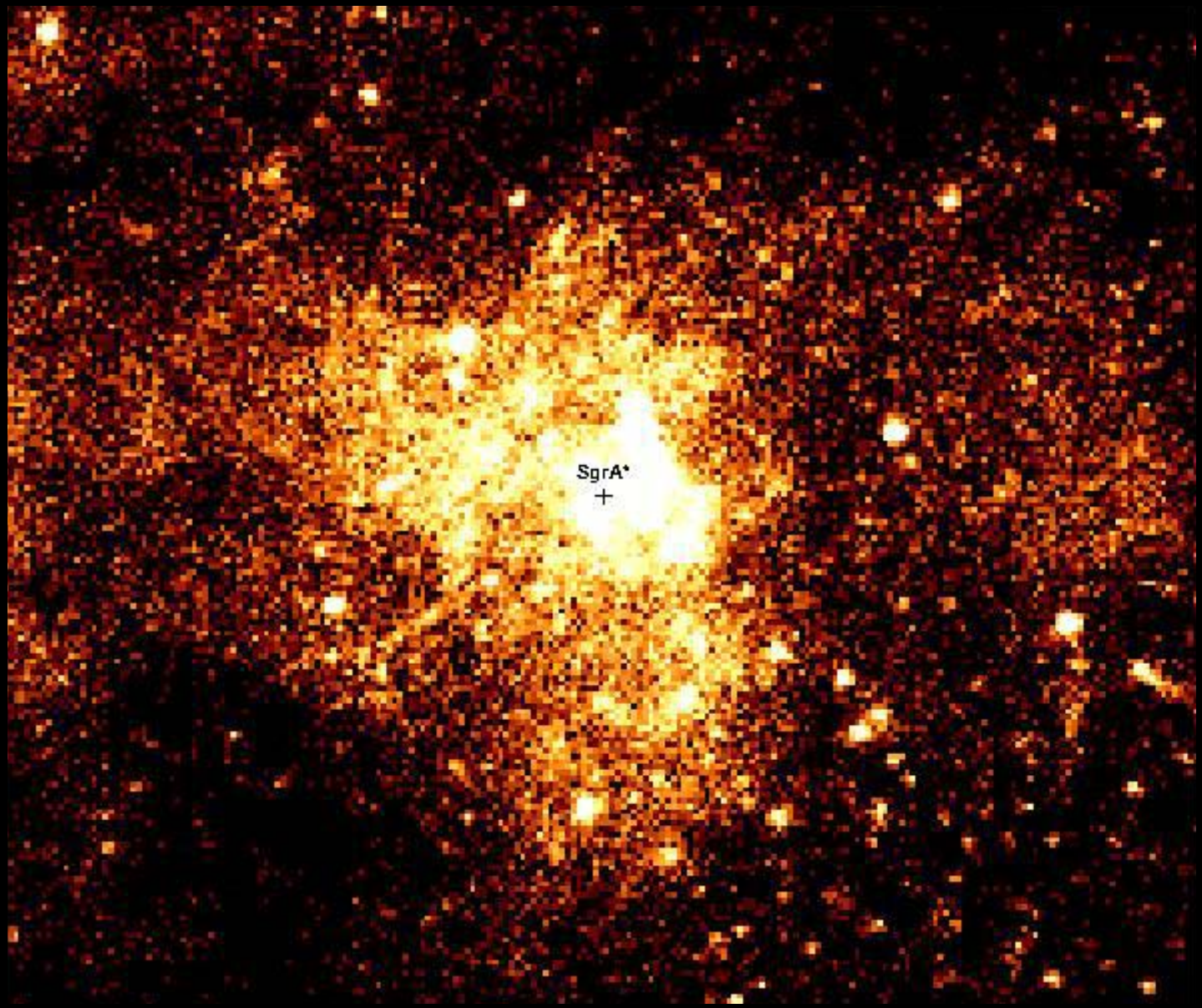


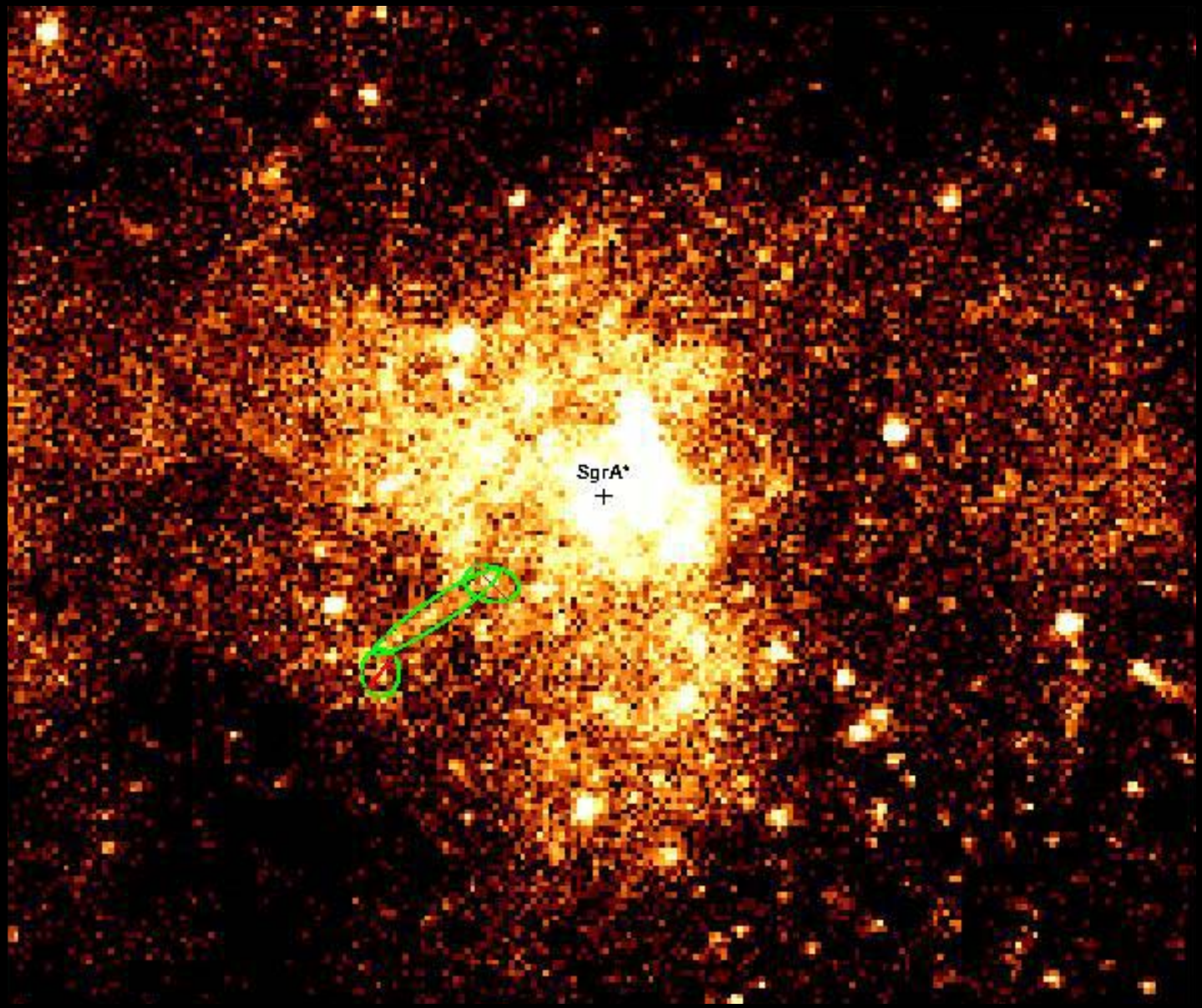
Ghez et al. (2003)

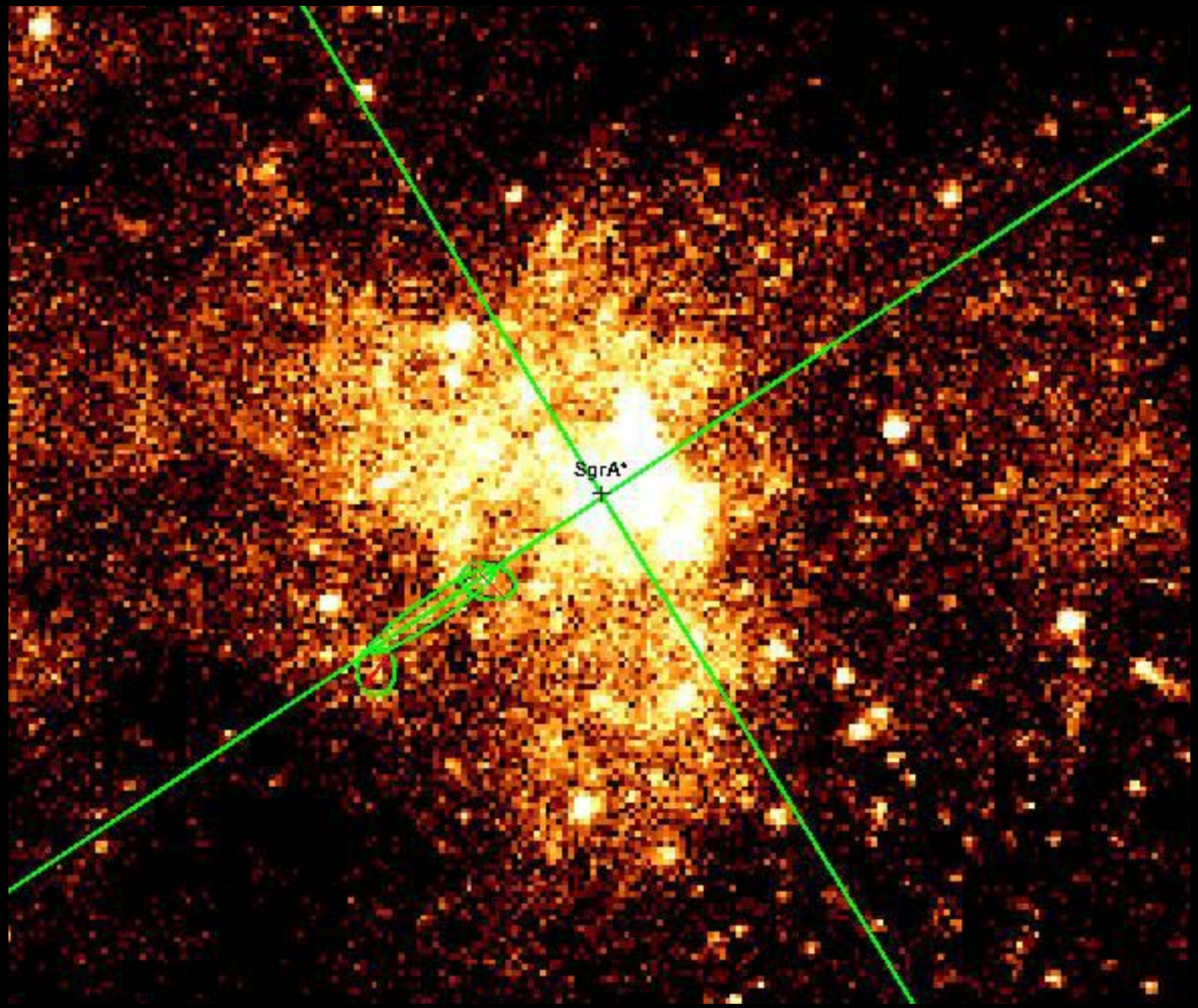
Spectral Energy Distribution of Sgr A*

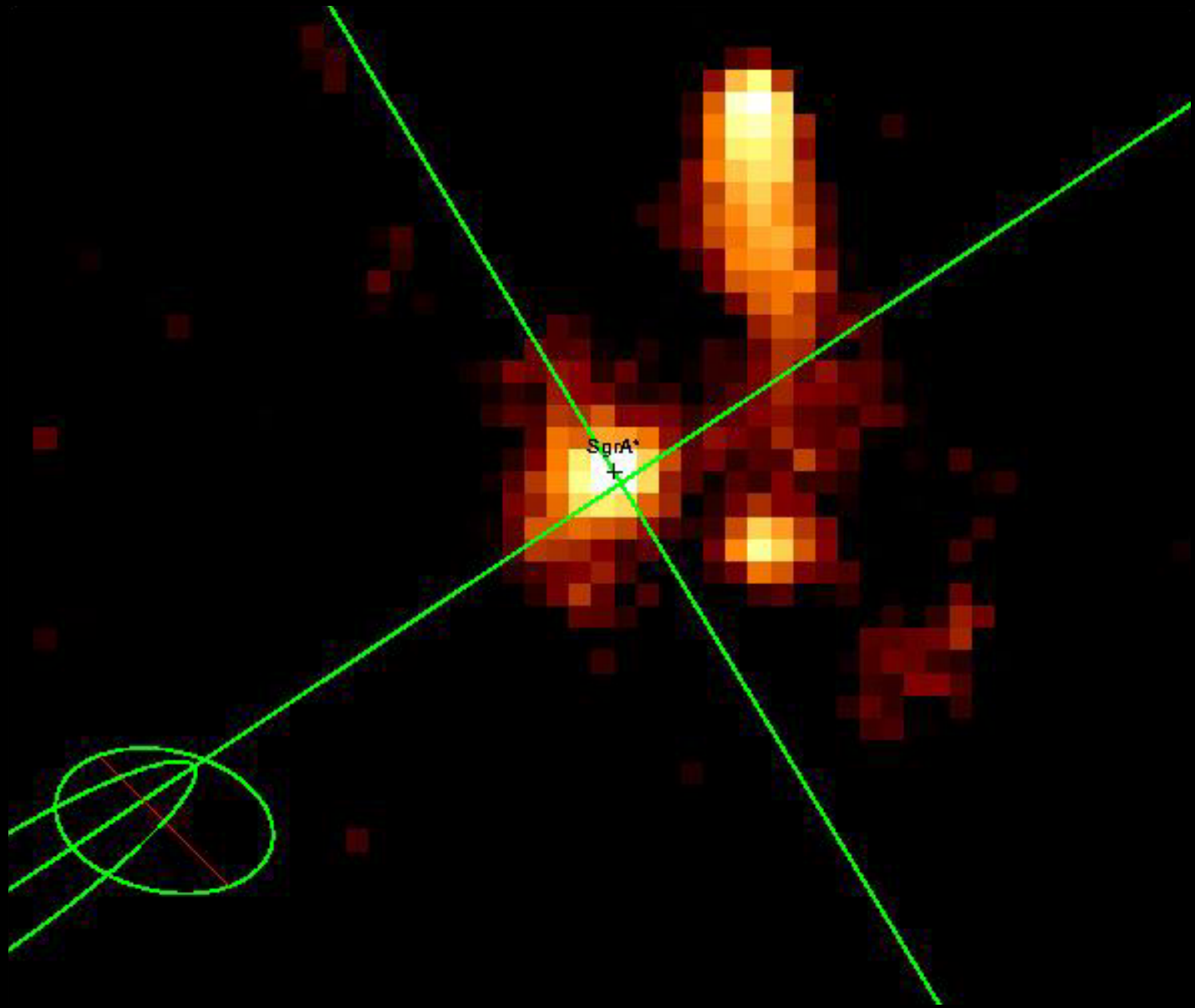


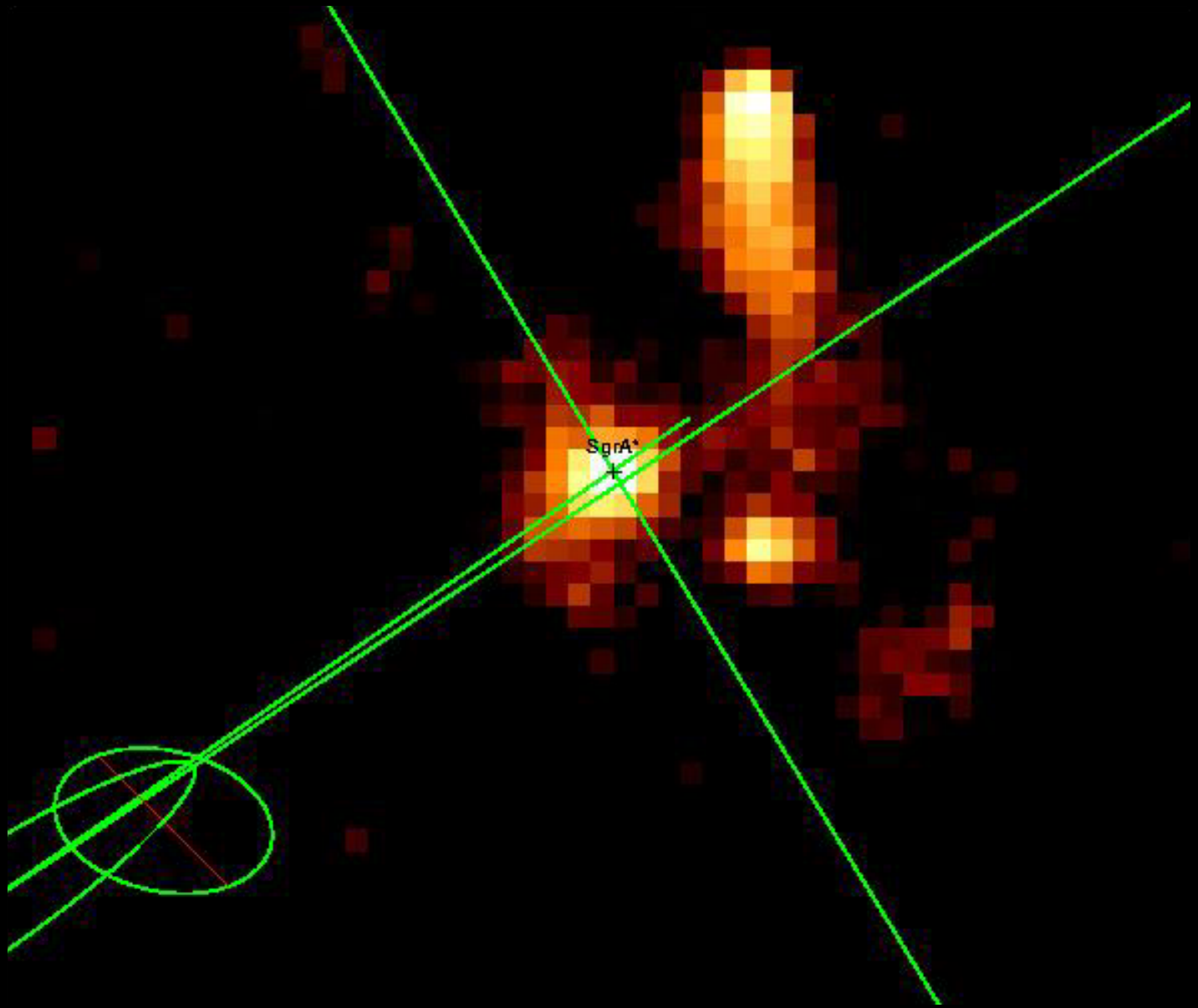
Spectral model: Yuan et al. 2003 ; L' fluxes: Ghez et al. 2003

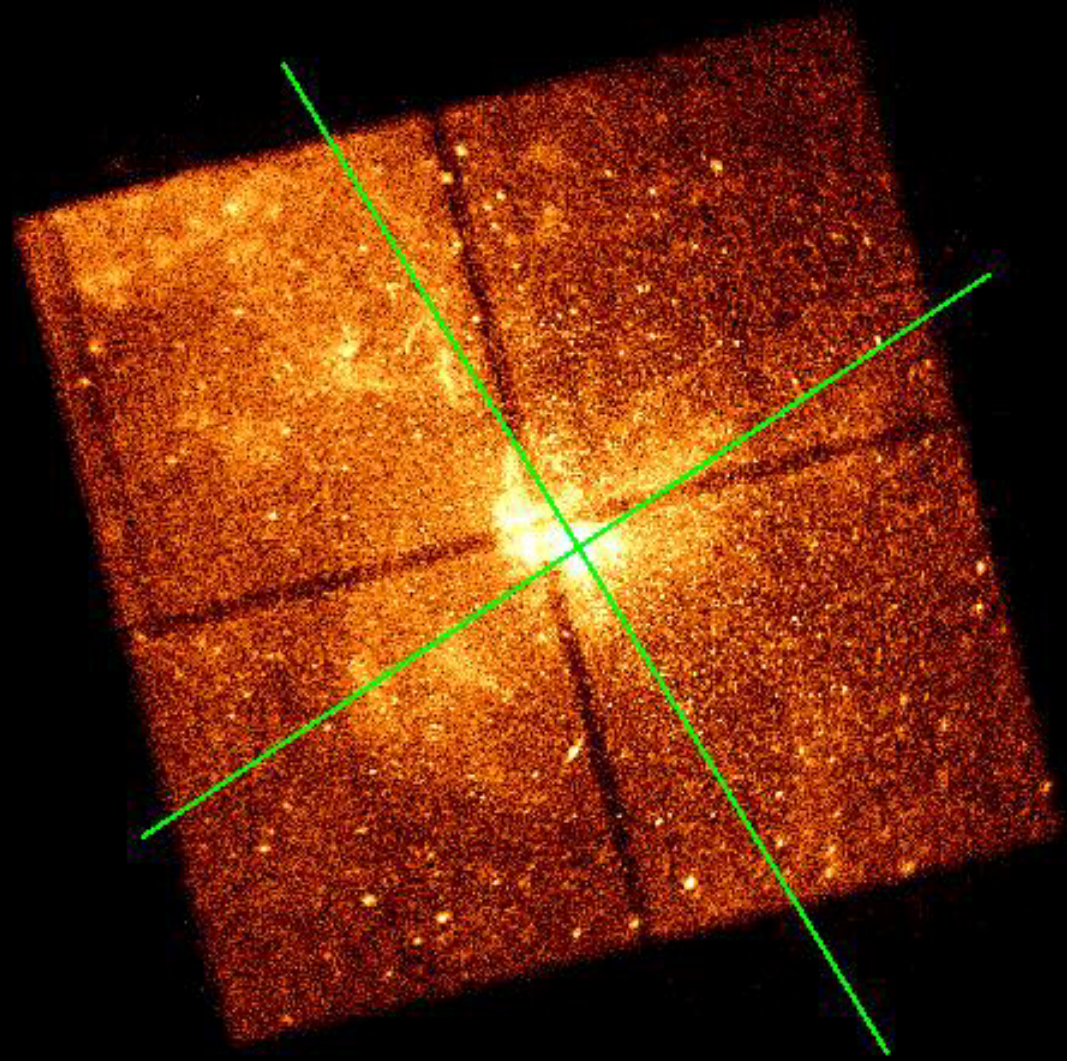

SgrA*


SgrA*


SgrA*

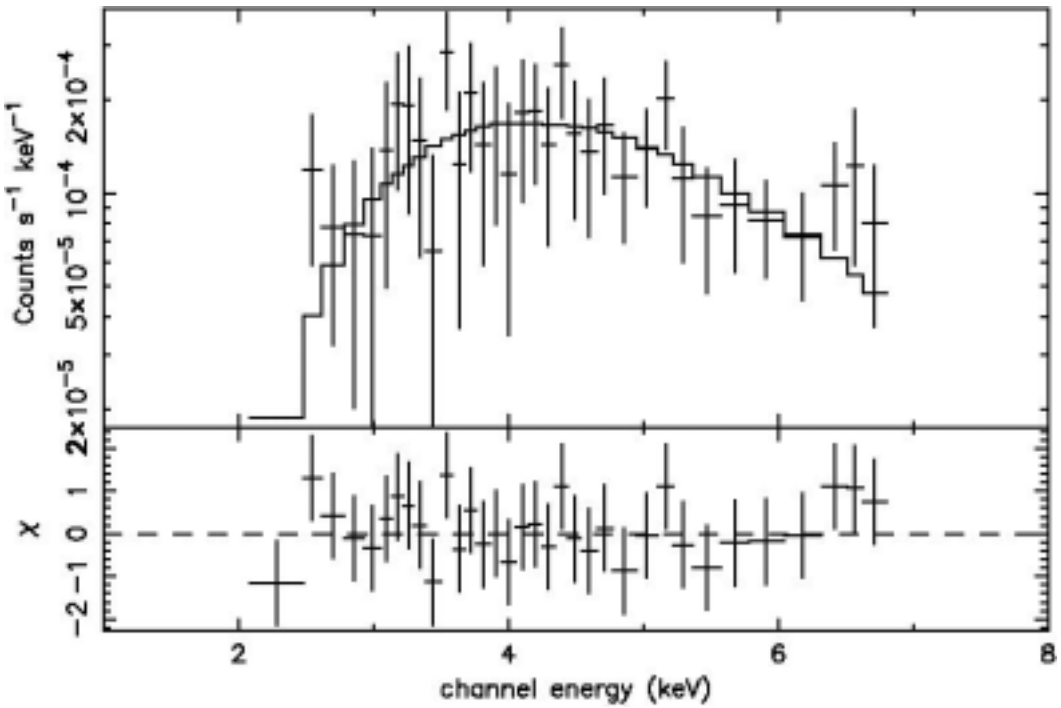

SgrA*


SgrA*



Spectrum of Possible Jet-like Feature Near Sgr A*

Absorbed Power-law Model – Dust Corrected



Gamma = 1.8

$N_H = 8.0 \times 10^{22}$ cm^{-2}

$L_X = 3.4 \times 10^{32}$ erg s^{-1}

Summary – X-ray Jet

- Discovery of an apparent X-ray jet from the Milky Way's central black hole
- Not seen in other wavebands
- Jet is 1 light-year long and located 1.5 light-years from the black hole
- Jet aligned with large-scale bipolar X-ray lobes
- Lobes may be due to past ejections or outflows from the supermassive black hole
- Suggests we are seeing "fingerprints" of activity over the past few thousand years
- X-ray flares tell us about the current activity

Conclusions

- Rapid, large-amplitude X-ray flares are not accompanied by significant radio and mm-band variations
- Sgr A* has now been detected in IR, and is variable on timescales of ~1 hr
- Future efforts
  - Continue coordinated multiwavelength monitoring to detect simultaneous X-ray and IR flares
    - Identify emission mechanism and constrain physical parameters (e.g., mag field strength, Lorentz factor, particle density near event horizon)
  - Push multiwavelength monitoring to sub-mm and MIR/FIR